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Commanders' Display of Terrain Information: Manipulations of Display Dimensionality and Frame of Reference to Support Battlefield Visualization

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Abstract

To gain a better understanding of the effects of display dimensionality and frame of reference on battlefield commanders' ability to understand the constraints of battlefield terrain, we constructed three electronic map displays, depicting both flat and mountainous terrain, and studied their effects on making various types of tactical judgments. U.S. Military Academy officers were presented with a two-dimensional (2D) contour display, a three-dimensional (3D) static, exocentric display, and a 3D interactive display of various battlefield situations (i.e., friendly and enemy units, travel paths, destinations) and were asked to make judgments regarding unit mobility across the depicted terrain, relative distances between units and or destinations, and line of sight (LOS) to specified locations. Officers were asked to make judgments as quickly and accurately as possible, while taking into account pre-defined mobility rules that had been distributed before the actual experimental session and were available throughout the study. In addition, officers were asked to provide verbal confidence ratings of having responded accurately to individual judgments. Results showed performance trade-offs in making the three tactical judgments, depending upon electronic map display format used. Distance judgments were best served by the 2D display, while the 3D interactive display best supported LOS judgments. Officers' performance in making mobility judgments was affected by the degree of vertical development of the depicted battlefield terrain. The relationship of participants' spatial ability to their performance in making tactical judgments and using interactive display capabilities is also discussed. When participants were provided with interactive viewpoint tools, there was a trend toward less frequent use (maneuvering) for officers with higher levels of spatial ability. It seemed that officers were relying more on their own perceptual and cognitive strengths to make judgments rather than taking the time and effort to use the display functionality. Since performance did not improve with greater use of the interactive tool of viewpoint positioning, it is possible that officers with lower levels of spatial ability might have compensated for these lower levels by increasing tool use, thereby preserving performance.

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INTRODUCTION

January 14, 1991, signified the dawn of a revolution in modern warfare. It marked the beginning of the Persian Gulf War, the integration of information technology, and the battlefield that would forever change the face of military combat. The technology now enabled commanders and troops to determine the exact position of enemy units in real time with global positioning system (GPS) technology, to disseminate critical information to troops separated by hundreds of miles of desert in a matter of seconds, and to deliver the attack of a full squadron with a single helicopter (Scheer & Englehardt, 1997). These technological advancements proved extremely effective in defeating the Iraqi forces during the Gulf War but have left the Army facing a new set of challenges for the battlefield of the 21st century.

With rapid development of advanced technology comes the increasing availability of massive amounts of information. Each new development provides increasingly more raw data to the Army commander. The battlefield environment is complex, requiring commanders' careful consideration of incoming information in order to make timely decisions regarding the current and future battle situation. Any inaccurate decisions may have potentially lethal consequences. Coupling the complexity of these tasks with human information processing limitations, the need for assisting the commander becomes readily apparent. Research from the disciplines of cognitive engineering and psychology has offered empirical evidence for various display methodologies that can assist operators by reducing the effects of information processing bottlenecks and by capitalizing more on humans' perceptual strengths. Exploiting principles of ecological interface design and proximity compatibility in display design can produce interfaces that support battlefield commanders in the appropriate "information extraction," rather than just increasing "data availability" (Bennett & Flach, 1991).

Although substantial strides have been made toward developing an understanding of the battlefield commanders' tasks, information processing limitations, and the contributions of display design to meet these demands, much research is still needed to make this understanding complete. Our research effort attempts to further that understanding by examining an aspect of military combat that has received little empirical investigation, yet remains a fundamental and critical aspect of any battle situation: the commanders' visualization of battlefield terrain.

The battlefield terrain has "an immense influence on how the battle will be fought. It can provide opportunities and impose limitations, giving a decisive edge to the commander that uses it best" (Department of the Army, 1993b). Various terrain features can be strategically used by the commander to provide security for his or her own forces or in other circumstances for attacking the enemy. Therefore, it becomes necessary to fully understand the types of terrain representations that can best support battlefield commanders' needs.

A lot of effort has been made to "digitize" the battlefield and offer the commander virtually all the technology that money can buy. Various military organizations harnessed existing technology and began creating their own display systems to enhance commanders' visualization of the battlefield. The Battlefield Planning and Visualization System of the 525th Military Intelligence Brigade, for example, provides for the integration of elevation data, map overlays, image overlays, and three-dimensional (3D) terrain databases. With this system, military personnel can access live information feeds, pull current friendly and enemy situations from databases, animate units, and produce a moving picture of the battlefield (Department of the Army, 525th Military Intelligence Brigade, 1997). Phoenix, a component of the Army's Force XXI vision, is yet another emerging technology for visualizing the battlefield. Phoenix's capabilities include scalable map displays, tracking of friendly and enemy forces, dynamic distributive overlays, interactive graphics, 3D terrain visualization, and video teleconferencing capabilities (Jackson, 1997). The capabilities provided to commanders by visualization systems such as these are virtually endless. Yet, what is lacking is empirical validation for the types of display technology that can actually support commanders' changing tasks and needs when these commanders visualize the terrain and those types of display technology that do not.

The Task of Terrain Analysis in Battlefield Planning and Ground Combat

In order to understand aspects of display design that can best be used for the purposes of terrain analysis in battlefield visualization, it is first necessary to gain a better understanding of what those tasks and information demands are for the battlefield commander. We discuss two aspects of the battle environment, namely, battlefield planning and ground combat, and the types of tactical judgments that are critical to these operations. These judgments include assessing mobility, accurately determining relative locations of friendly and enemy units and certain targets, evaluating line-of-sight (LOS) visibility, and object and terrain recognition.

Battlefield Planning

Topographical teams and support staffs are responsible for conducting thorough

terrain analyses to support commanders in battlefield planning. This analysis can range from elevation calculations and specifications of restricted and unrestricted terrain to soil and vegetation data, depending upon the specific needs of the commander and the battle situation (Department of the Army, 1990). The commander's task of terrain analysis for the purpose of battlefield planning is usually twofold: (a) the analysis of the military aspects of the terrain and (b) evaluation of the terrain's effects on military operations (Department of the Army, 1994). Military aspects of the terrain are defined as observation and fields of fire, concealment and cover, obstacles, key terrain, and avenues of approach. Observation, fields of fire, and concealment and cover all involve the commander's ability to identify those areas that allow the unit to visually "see" the enemy or target and effectively fire upon them or it, as well as those areas that can effectively conceal U.S. soldiers from the enemy and offer protection from fire when necessary. Identifying obstacles in the battlefield environment is crucial to the commander's development of plausible routes or avenues of approach to take in order to reach specified objectives. Examples of natural and man-made terrain features that can impede troop movement include rivers, lakes, steep slopes, buildings, and cities. In addition to those aspects of terrain that are desirable to avoid, commanders also need to identify key terrain or areas of the battlefield environment that are desirable to obtain in order to have a decisive advantage over the enemy. What is deemed key terrain by the commander depends greatly on the nature of the battle at hand (Richbourg & Olson, 1996).

The second component of terrain analysis involves integrating this knowledge of military aspects of the terrain with the dynamics of the current battle and specific rules governing military operations. This requires taking the battlefield into consideration not only from a friendly perspective but analyzing possible enemy actions as well. Rules governing the maneuvering speed of different units, their weapons' ranges, and capabilities in traversing various types of terrain are also critical to successful battlefield planning. It is important to emphasize that during these planning phases, the commander is operating from a perspective "outside" the actual terrain or battlefield environment looking in, rather than as an actual part of it, as is the case within the context of ground combat.

Ground Combat

Once battle plans have been made, terrain continues to play a crucial role in the success of military operations. Lower level commanders (e.g., company - platoon) analyze the terrain in order to successfully navigate to key objectives and execute those operations specified by higher level commanders during battlefield planning. This type of way finding and navigation relies heavily upon the ability to recognize critical features and terrain as they are depicted on the

maps used to navigate through the battlefield as well as in the surrounding environment. Army doctrine outlines several guidelines for conducting terrain analysis for navigation, which they term "terrain association" (Department of the Army, 1993a). These include (a) planning the route, (b) knowing where you are, (c) recognizing the objective, and (d) staying on the route. Planning the route relies upon many of the same previously mentioned skills that higher level commanders use in battlefield planning to assess possible avenues of mobility or the key piece(s) of terrain that are the specific unit's objective to attain, but the commander is now performing these operations while immersed in the battlefield environment.

The navigator should always know where he or she is in relation to directional orientation, the direction and distance to the objective, other landmarks and features, restrictive terrain or potential hazards, and both the navigational possibilities and limitations of the terrain that lie between him or her and the objective (Department of the Army, 1993). Possessing this knowledge and the ability to recognize these features will in turn affect his or her ability to stay on the designated route. Army doctrine on map reading and land navigation recommends that navigators orient their maps to match the terrain as they proceed along their route. Both the map and environment should be examined to identify major terrain features such as hilltops, valleys, ridges, saddles, and depressions, as well as symbology denoting the presence of man-made features. Man-made objects that can be used to aid way finding and navigation include buildings, roads, bridges, and power lines.

Tactical Judgments

As can be seen, a multitude of factors must be taken into consideration when battlefield terrain is analyzed for battlefield planning and ground navigation purposes. The success of these operations relies to a great extent upon the commander's perceptual and cognitive abilities in making various judgments, based upon this terrain information. We now focus our discussion on four different types of tactical judgments that are critical to these battlefield operations: (a) assessing mobility, (b) accurately determining relative locations of friendly and enemy units and certain targets, (c) evaluating LOS visibility, and (d) object and terrain recognition. Each of these types of judgments is discussed in detail. However, since our present paradigm is constrained to battlefield planning operations, we will not be explicitly looking at the issues of object and terrain recognition in ground navigation.

Assessing Mobility

Of key importance in the analysis of terrain is the determination of possible avenues for troop movement, whether the end goal is to attack the enemy, secure a piece

of terrain, or deliver resources to friendly troops. These judgments depend upon an accurate understanding of the overall configuration of the terrain in conjunction with existing constraints governing troop movement (e.g., speed of travel or maximum terrain gradient capable of being traversed). To accurately make these judgments, the commander must have a well-developed awareness of the current surroundings. The accuracy in estimating time-distance relationships of troop movement across the terrain is essential in discriminating successful paths for movement from less efficient ones.

Accurately Determining Relative Locations of Friendly and Enemy Units

The capability to accurately estimate relative distances between friendly and enemy troops, a unit and its specific military objective, or a unit and a potential obstacle or treacherous area of terrain is crucial to successful battle planning and ground navigation. Accurate judgments of this type also prove useful in determining susceptibility to enemy fire or friendly capability of penetrating enemy forces.

Evaluating LOS Visibility

The Army defines LOS as "an unobstructed view from point A to point B" (Department of the Army, 1993). Assessment of LOS visibility can affect decisions such as where observation posts and signal stations are positioned, as well as identification of terrain features that can offer protective coverage from the enemy (Musham, 1944). An accurate assessment therefore relies heavily on an understanding of the terrain from different perspectives, friendly as well as enemy. Since the commander is often unable to occupy the physical location upon which LOS to another location is being determined, he or she must use topographical maps to assess the possibility of visibility. Crucial components to assessing visibility include the unit or observer's location and height, target location and height, and characteristics of the intervening terrain (Ray, 1994). According to Ray (1994), the question to be asked by the commander in order to assess visibility should be, "What can I see if I set up here?"

Object and Terrain Recognition

The soldier who can rapidly identify and discriminate among the different terrain and features of the battlefield, "knows how these features are mapped, can begin to visualize the shape of the land by studying the map, can estimate distances, and is the one who will be at the right place to help defeat the enemy on the battlefield" (Department of the Army, 1993). Possessing these skills is critical for commanders at lower levels, who regularly engage in way finding and navigation through the terrain. Using their contour maps, commanders must be

able to quickly visualize the terrain they will be navigating through and likewise be able to convert their 3D surroundings into the contour patterns depicted on their maps to accurately identify a current location (Barsam & Simutis, 1984). Using this information supplied from the map and surrounding terrain, commanders must also be able to determine and accurately estimate direction and distance (Department of the Army, 1993). The complexity or degree of vertical development of the battlefield also plays a key role in determining the commander's ability in making each of these types of judgments.

Features of Display Design to Support Terrain Analysis in Battlefield Visualization

Given that we understand some of the issues in battlefield management, we are specifically interested in examining issues of terrain information displays. Two features of display design that can affect the commanders' ability to visualize the battlefield terrain are dimensionality and frame of reference. Research from various domains is discussed, examining the effects of each feature on making the following types of judgments: (a) location of targets in the air, (b) location awareness of points relative to surfaces, and (c) recognition (envisioning) of the shape of terrain. While a and b are not as directly related to ground operations, there is a considerably greater research base regarding display effects on these judgments, and thus, a and b provide a basis for making predictions of display effectiveness and for understanding human perceptual limitations.

Dimensionality

Military terrain information has traditionally been depicted in a 2D format, with contour lines delineating the elevation of terrain features. Figure 1 illustrates a typical military contour map with a sketch of the actual terrain depicted below (Musham, 1944).

The benefits of this 2D format for battlefield commanders are twofold. First, the top-down viewpoint depicts a broad area of terrain, providing a view of terrain in the range of possible directions (i.e., in front of a unit's present location, behind it, to the east, etc.). Secondly, the "graphical compression of the vertical axis" in 2D contour maps results in an unambiguous representation for making precise, relative lateral position judgments (Wickens & Prevett, 1995). However, 2D contour maps do have several disadvantages. A considerable amount of mental gymnastics are required to transform the information provided in this 2D format into a coherent, 3D picture of the terrain (Wickens, 1992). These kinds of transformations required with 2D contour maps for military operations have been described as "labor intensive, error prone, and time consuming" (Ray, 1994). Much training and experience are required to accurately and

rapidly decipher the contour map symbology and envision the various aspects of the terrain (Barsam & Simutis, 1984).

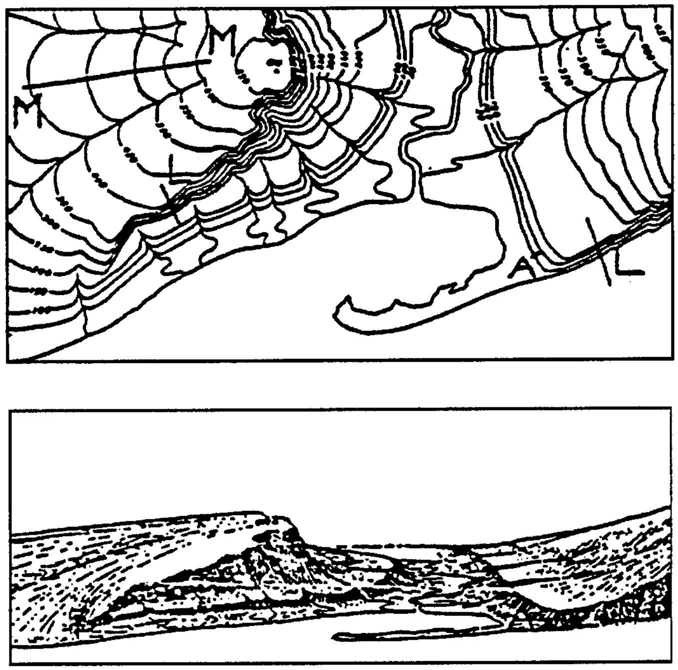

Figure 1. Depiction of a typical military contour map (top); sketch of the actual terrain depicted in the map (bottom) (adapted from Musham, 1944).

Three-dimensional portrayals, on the other hand, can readily provide terrain information to the commander in a format that is compatible with the actual terrain being represented (Wickens, 1992; Wickens, Todd, & Seidler, 1989; Hickox & Wickens, 1996). This eliminates the need for extensive training in interpreting contour map symbology and error-prone envisioning of actual terrain features since this information has been integrated into one representation. However, with the benefits of 3D displays also come certain perceptual biases.

McGreevy and Ellis (1986) and their colleagues identified various perceptual biases associated with 3D perspective displays, one of which they termed the "3D-to-2D projection effect." This bias stems from the difficulty in projecting a 3D space onto a 2D surface. This results in ambiguity along the LOS, or viewing axis, in that a single point on a 2D surface can represent an infinite number of 3D positions (Wickens, 1995; Gregory, 1977). These ambiguity effects can be reduced to a certain extent with the inclusion of additional depth cues (Wickens, Todd, & Seidler, 1989). However, additional perceptual biases, namely, foreshortening and resolution loss, can still exist.

Foreshortening refers to the fact that the amount of information conveyed by cues, regarding displacement in depth relative to the screen surface, is perceived as being smaller than the amount of lateral or vertical displacement. This leads to a distorted perception of objects within the display as being closer to the display surface, which is in effect "rotated" to a plane more parallel with the viewing surface than in actuality (see Figure 2). This phenomenon can lead to over-estimation in judging altitude relative to distance, proving especially detrimental when judgments of mobility are made across terrain viewed "head-on" in the display. Referred to as "slant overestimation" (McGreevy & Ellis, 1986; Perrone, 1982), slopes of the terrain will tend to be perceived as being much steeper than they actually are.

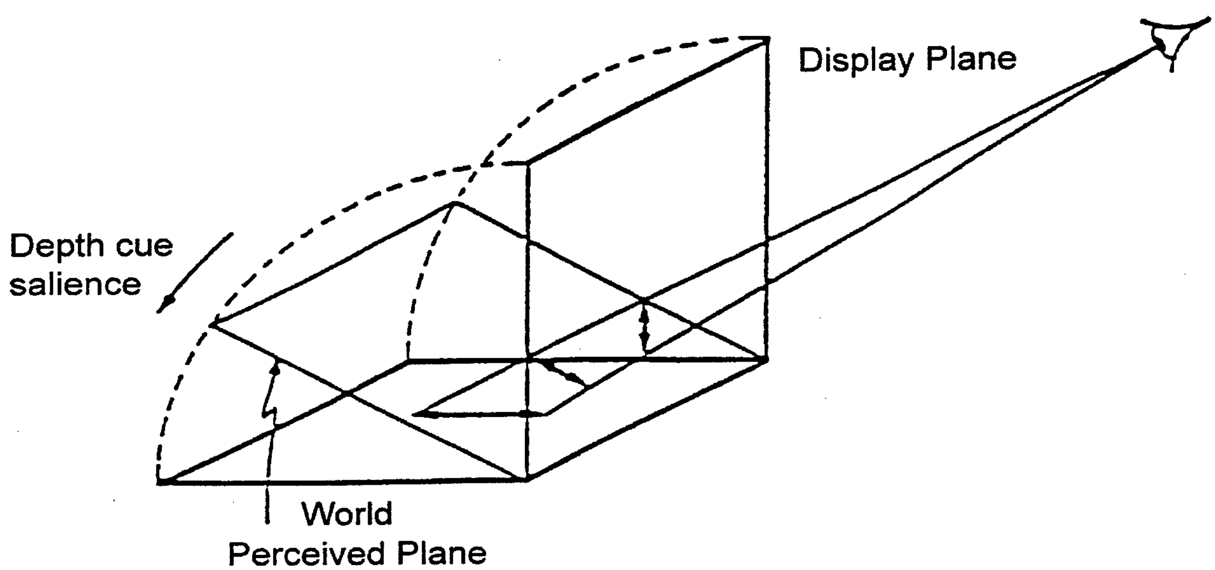

Figure 2. Illustration of perceptual distortion in 3D displays, in which a vector is rotated to an orientation more parallel with the viewing surface (adapted from Wickens, Todd, & Seidler, 1989).

Resolution loss results from the fact that changes in position in depth, in comparison to changes in lateral or vertical separation of equal magnitude, are represented by smaller changes in visual angle. Estimation of position for tasks involving location awareness as well as tracking in depth will suffer from this degradation in resolution (Wickens, 1999; Boyer & Wickens, 1994).

Research in the fields of data visualization, aviation, and air traffic control has investigated the issue of 2D and 3D display formats for supporting a variety of tasks and the corresponding costs and benefits associated with them. Since little research exists regarding these issues in the domain of battlefield terrain visualization, we have extended our review to consider

relevant studies in the design of displays in these fields. However, we caution that the vertical axis in aviation (pilot and air traffic control) displays has a somewhat different semantic meaning. In particular, in most aviation environments, its relevance is the danger of occupancy by two (or more) aircraft of the same altitude, in lateral proximity. In ground combat and battlefield planning, however, its relevance appears to be threefold: (a) mobility will be degraded by the amount of vertical development in terrain, (b) LOS visibility can be greatly influenced, positively or negatively, by terrain, and (c) for commanders at lower levels (company-platoon), who are engaged in way finding and navigation, the role of 3D displays in object and terrain recognition becomes important (Hickox & Wickens, 1996). We consider group studies by different classes of tasks, but we focus here on awareness and understanding of location, rather than on guidance. In the following, we consider first judgments of point location in the air, then judgments of point location relative to the ground or surface, and finally recognizing or envisioning the shape of terrain.

Location of Targets in the Air

In two separate experiments, Merwin, O'Brien, and Wickens (1997) compared 2D and 3D cockpit displays of traffic information, finding a benefit for the coplanar display over the perspective view in the ability to precisely locate objects in space. Flight instructors were instructed to fly as directly as possible to way points, while avoiding the creation of an actual or predicted conflict with other "intruder" aircraft. Aircraft within the displays were equipped with a predictor line, indicating the future trajectory of the aircraft, and a threat vector extending from ownship's[1] predictor line in the direction of intruder traffic. A predicted conflict resulted when the threat vector extending from ownship contacted an intruder's protected zone, with an actual conflict arising when this threat vector contacted the intruder aircraft itself. Results showed that the coplanar display supported better conflict resolution, in terms of fewer predicted conflicts with primary traffic and fewer actual conflicts with secondary traffic. Increases in conflict rates with the 3D perspective display were especially prevalent when intruder traffic was ascending or descending rather than in level flight.

Olmos, Wickens, and Chudy (1997) also found a benefit for the 2D format when examining issues of display dimensionality to support aircraft navigation and tactical awareness. Pilots were instructed to fly to various way points within a 3D space, using either 2D coplanar or 3D exocentric and egocentric display formats. As pilots flew their missions, various traffic targets appeared in the volume, which required pilots to estimate the targets'

[1] The platform or vehicle in which the operator resides.

bearing, range, and elevation angle relative to ownship. Results showed a cost of the 3D display formats when vertical information was estimated, with higher accuracy for the 2D coplanar display when pilots made judgments of target altitude relative to ownship.

This cost of ambiguity within the 3D display surfaced again, this time when the authors examined pilots' location awareness during a simulated landing task. Wickens and Prevett (1995) asked pilot subjects to fly simulated approaches to landing, following along a flight depicted in either a 2D coplanar format or one of four 3D display formats, varying in the level of egocentricity. In addition, pilot subjects were probed about various measures of awareness at intermittent periods throughout the experimental session. At certain times, the simulation was halted and participants were asked questions regarding the relative location of objects in space, for example, "Is the peak of the terrain feature to your left or right, higher or lower than the flight path?" Pilots were more accurate when responding to these judgments using the 2D display format than the 3D format.

Similar to Wickens' and Prevett's (1995) paradigm, Wickens, Liang, Prevett, and Olmos (1996) measured pilots' flight path tracking and ability to maintain awareness of the location of surrounding features in a simulated landing task. However, in Wickens, Liang et al. (1996) study, display dimensionality was now coupled with the manipulation of map rotation, providing subjects with fixed and rotating 2D coplanar and 3D display formats. Measures of pilots' awareness of surroundings included determining the relative bearing of terrain features nearest their aircraft and the altitude of these features (in terms of higher or lower than their aircraft). Results did not show a benefit for either display format in determining relative bearing of terrain features. On the other hand, pilots judged the altitude of terrain features (relative to ownship) to be faster when viewing the 3D displays but were more accurate with the 2D coplanar format.

Olmos, Liang, and Wickens (1997) continued the study of 2D and 3D display formats within the approach to landing paradigm used by Wickens and Prevett (1995) and Wickens, Liang, Prevett, and Olmos (1996). However, two modifications were made in the previous studies. This included the portrayal of terrain on a wide screen display, simulating the forward field of view (FFOV) from the aircraft cockpit, and the addition of a 2D "wedge" display. This display format used the cognitive engineering principle of visual momentum (Woods, 1984; Banks & Wickens, 1997) by displaying a wedge in the planar view of the 2D display that corresponded to the pilot's FFOV presented on the wide screen display (Aretz, 1991). Pilots' awareness of their surroundings was probed by asking them to determine the

relative bearing to nearest terrain features (designated by purple flags), as well as the altitude of the flag relative to ownship. In addition, at unexpected times throughout the experimental session, a single hot air balloon appeared on both the wide screen and map display. Upon the appearance of the balloon, pilots were required to compare wide screen and map display views, determine if a discrepancy existed between the two views, and indicate whether that discrepancy was one of lateral position, vertical position, or both. Results again showed a benefit for the 2D display format, both in terms of vertical judgment accuracy when comparisons were made between the map display and the FFOV, and in faster responses to vertical judgments of surrounding terrain features relative to ownship.

Other studies of pilots cockpit display of traffic information along with those of air traffic control display have investigated the utility of the 2D and 3D display formats, but now the perspective display is compared with a 2D uniplanar representation of the airspace, rather than the 2D coplanar display discussed before. With the 2D uniplanar displays, altitude was represented digitally. In one such study conducted by Wickens, Miller, and Tham (1996), air traffic controllers and pilot subjects viewed 2D and 3D displays of a simulated airspace and were asked to determine whether requests made by an aircraft depicted on the display would conflict with other aircraft within the airspace. Requests from aircraft could include a heading change, altitude change, or both, with a conflict arising if a change resulted in a breakdown of aircraft separation (fewer than 1000 feet vertically or 3 miles horizontally). Results showed that both display formats equally supported the accurate discrimination of "safe" paths (i.e., ones that did not create a separation conflict) from unsafe ones. While no difference was seen between display formats in the amount of time it took pilot subjects to evaluate requests, air traffic controllers were faster with the 2D display format, especially when requests included combined changes of heading and altitude.

Ellis, McGreevy, and Hitchcock (1987) compared similar 2D uniplanar and 3D perspective display formats within the context of cockpit displays of traffic information and found a benefit for the perspective display for precise location judgments. Pilots viewed a series of traffic situations and were required to determine if a conflict would take place, in terms of a violation of spacing between an intruding aircraft and ownship, and to select the appropriate avoidance maneuvers. Results showed that the 3D perspective display format led to faster response times. The 3D format also led to significantly more vertical maneuvers than the plan view format. However, unlike its 3D counterpart, the 2D display of traffic represented altitude information alphanumerically.

In summary, research within the aviation and air traffic control domain has tended to show that 2D display formats are more beneficial than 3D displays in supporting relative position judgments. Most of the costs with the 3D display arise when vertical behavior is unconstrained, requiring the accurate estimation of position along both the vertical and lateral axes.

Location of Air Targets Relative to the Ground or Surface

Equally as important as pilots' awareness of the relative locations of objects within a vertically unconstrained 3D "volume" or air space is an awareness of locations within more constrained environments, particularly with respect to hazard volumes in the air, such as weather or terrain on the ground. This piloting task is similar to the task of battlefield terrain visualization, in which battlefield commanders must also assess viable routes through or must negotiate around hazards to reach a specified target. In the realm of battlefield planning, however, these hazards are restrictive terrain features within the battlefield environment rather than weather formations within a given air space.

Employing the same paradigm as Merwin and Wickens (1996), O'Brien and Wickens (1997) extended investigation of display formats to support pilots' awareness of traffic, including the ability to avoid weather hazards. Instead of encountering additional intruder traffic as in Merwin and Wickens' study, pilots had to detect and initiate appropriate avoidance maneuvers for various weather formations represented in the displays. Results indicated a benefit for the coplanar format in terms of pilots' ability to accurately estimate separation from weather hazards and to initiate successful avoidance maneuvers, resulting in fewer actual conflicts with the weather formations than the perspective display formats.

Boyer and Wickens (1994) examined the issue of weather avoidance by comparing the 3D perspective format to the 2D coplanar format and found more comparable performance between the two formats. Subjects engaged in a route-planning task, in which they were to chart a course around or through weather formations to reach a specified target within the air space. Both 2D and 3D displays were compared in this study, with results indicating that both formats equally supported the creation of accurate routes. Further analysis showed that the 2D format supported faster planning times as well as shorter lateral distances taken to reach target markers. The authors attributed these benefits to possible ambiguities inherent in 3D displays.

May, Campbell, and Wickens (1996) also looked at 2D planar and 3D perspective representations of weather. Pilot and air traffic controller subjects were tasked with (a) determining as quickly as possible whether aircraft depicted in the displays would penetrate

weather formations if continuing on course and (b) re-vectoring aircraft within the display to desired locations around weather hazards. If an aircraft continuing on course would penetrate weather formations, subjects were required to designate the point of penetration and issue a vector to the aircraft that would provide clearance from weather conflicts. If penetration of weather formations would not occur, subjects were required to designate that point where the aircraft and weather hazard would be closest and to estimate both the vertical and horizontal distances between the aircraft and weather hazard at that point.

Both display formats supported equally accurate performance in determining whether aircraft would penetrate weather formations if continuing on course, as well as determining where the point of closest pass to the weather hazard would be if penetration did not occur. Both display formats were also equally accurate in supporting the issuance of safe vectors to aircraft in order to circumnavigate weather hazards, with the 2D display resulting in more headings being issued but with minimum deviations from the initial course. This finding parallels that of Boyer and Wickens (1994) in which the 3D display resulted in more "conservative" routes around weather hazards.

Several studies have also investigated the use of 2D and 3D displays for avoiding collisions with hazards on the ground, namely, terrain. May, Campbell, and Wickens (1996) also applied a similar paradigm to the one previously described for weather avoidance to the location and avoidance of terrain features. Pilots and air traffic controllers were also tasked with determining as quickly as possible whether aircraft depicted in the displays would collide with the hazard (now terrain) if continuing on course and with re-vectoring aircraft within the display to desired locations around the hazards. In addition, subjects were given scenarios in which a "lost" plane appeared, requiring them to determine whether continuing on its flight plan would be safe, marginally safe, or unsafe with respect to proximity to terrain. Results showed air traffic controllers to be more accurate in determining the lateral distance between aircraft and terrain with the 2D display format. Pilots, on the other hand, were equally accurate with both display formats. Participants were also faster with the 2D display format in classifying the safety of an aircraft's flight plan with respect to potential collisions with terrain. Similar to findings with the re-vectoring of aircraft around weather hazards, the results showed that the 2D display led to more vector insertions than the 3D display. However, in this instance, it led to more accurate performance than the 3D display.

In the previously discussed Olmos, Wickens, and Chudy (1997) study, as pilots flew to way points, they were required to avoid contact with terrain objects and radar

coverage zones as well as detect and avoid "pop-up" hazards, appearing at intermittent times throughout the trials. Avoiding collision with these objects relied upon pilots' accurate judgments of the bearing and altitude of these features relative to ownship. The results showed a benefit for the 3D exocentric display in terms of the number of times pilots actually contacted hazards and in terms of the detection and avoidance of pop-up hazards. Using the principles of cognitive engineering, the authors made several display enhancements and conducted an ensuing study. These enhancements included color coding of features within the 2D display and using a "wedge-like" predictor symbol in the 3D exocentric display to provide pilots with additional cues for estimating lateral and vertical clearances from terrain and air hazards. Results indicated a significant drop in the number of hazard contacts with the 2D display format to a level just about equal with performance with the 3D displays. Performance also equalized between the two 3D display formats for time required for pilots to detect and begin maneuvers to avoid pop-up hazards.

Moving from the aviation domain into the context of database visualization, McCormick and Wickens (1995) examined the utility of 2D coplanar and 3D formats in making precise judgments of locating objects in the database relative to the colored walls or "surfaces" of the environment. Participants were required to navigate to various target objects within the 3D volume as quickly and accurately as possible, while making various position judgments as they were presented randomly throughout the experimental trials. Results indicated that participants were significantly slower in responding to these judgments with the 2D display format and were less accurate. This finding contrasts results showing relatively equal performance with 2D and 3D displays within aviation contexts but may be to some extent attributable to the costs of scanning between the two displays within the 2D format.

In conclusion, when the location of targets was estimated relative to surfaces such as terrain or weather hazards, most results indicated few performance differences between the 2D and 3D display formats. When differences did occur, they tended to indicate that the 2D display was beneficial in pilots' more rapidly making judgments and more accurately estimating lateral separation between target and hazards (Wickens, 1995). The benefits of the 2D display appear to be diminished (but not necessarily eliminated) when the format is uniplanar (i.e., altitude represented digitally) rather than coplanar.

Recognizing (Envisioning) the Shape of the Terrain

As the commander navigates through the terrain, he or she must repeatedly compare features in his or her FFOV with a contour map of terrain to determine congruence between the two. This task is comparable to "same-different" object paradigms discussed in

psychological literature and to a pilot's task of navigational checking in air navigation. When performing navigational checking, pilots make repeated comparisons of features in their FFOV from the cockpit to features on the map to determine congruence in where they "think" they are and where they actually are (Hickox & Wickens, 1996; Aretz, 1991).

Hickox and Wickens (1996) examined the effects of dimensionality on this task by providing pilots with static images of a digitized scene containing roads, bridges, towns, mountains, and rivers on a computer display and asking them to compare these images with a more realistic, wide screen display depicting the pilots' FFOV. Pilots were required to determine as quickly and accurately as possible whether the depictions were of the same geographical location. The angle of elevation at which information was presented in the map and FFOV was varied, with results indicating higher accuracy at map elevation angles of 45°, essentially a 3D perspective view, than at 90°, a 2D plan view.

Williams, Hutchinson, and Wickens (1996) assessed pilots' abilities to envision the features of their surrounding environment from either 2D or 3D map representations, yet within the context of navigational (geographical) learning. Williams et al. (1996) compared the performance of pilot subjects in a transfer flight environment while varying the training methods used in the rehearsal flight. Pilots rehearsed either by studying a 2D map of the route to be flown, navigating through the environment using a 3D display, or passively viewing a rehearsal flight through the environment with the same 3D display. Those participants who studied a 2D map of the route to be flown in the environment during training had a better understanding of the overall environment than did those participants using 3D displays during rehearsal flights. The cost of training with the 3D displays may be partly attributable to most pilots' cognitive resources being allotted to the task of navigation rather than spatial learning, the latter process being enforced more through map study (Williams et al., 1996).

Finally, two studies move from the domain of terrain to that of visualizing (recognizing) the 3D shape of data points. Wickens, Merwin, and Lin (1994) asked participants to play the role of an economist looking at data sets from a database, depicted in either a 2D coplanar or 3D perspective format. Participants viewed several of these data sets (from the large database) to understand relationships among the variables of price, earnings, and debt. The participants were then asked questions about the data, which focused on singular dimensions of the data set as well as integrating across dimensions in order to make more global judgments. Significantly faster response times were found with the 3D display when participants made judgments that required the integration of database information. During tasks requiring

participants to recognize changes in relationships among variables, participants were more accurate with the 3D display than with the 2D displays, signifying a better overall understanding and visualization of the database.

McCormick and Wickens (1995) also found this benefit for the 3D display in making judgments regarding the overall configuration of target objects within the 3D data environment. Upon completion of navigating to and intercepting all target objects within the 3D volume, the screen blanked and participants were asked to determine the overall "shape" (i.e., pyramid, sphere) or distribution (i.e., all data points were higher next to a given colored wall) or data within the 3D space. Although both displays yielded relatively equal response times to these judgments, responses with the 3D display format were significantly more accurate.

Therefore, when tasked with determining the precise location of targets in the air, humans performed more effectively using 2D coplanar displays. When the environment is more constrained, the benefits of one display dimensionality over another are less clear. When costs and benefits of each format are considered, both displays seem to be roughly equal. However, when the user is trying to develop an understanding of the overall shape of the terrain or surrounding environment, there seems to be a distinct benefit for the 3D display.

Degree of Immersion

The frame of reference or viewpoint from which the observer views the environment in a display can vary from a rotating, highly egocentric one in which the observer is immersed within the environment (typical of virtual reality) to a static, exocentric viewpoint in which the view presented is seen from some fixed location above or behind the environment (McCormick, Wickens, Yeh, & Banks, 1997). The benefits of employing one particular frame of reference instead of another for displaying terrain information highly depend upon the tasks involved.

An immersive frame of reference presents information in the display that directly corresponds with the information presently in the FFOV of the commander who is actually navigating through the terrain. Two advantages of an immersive frame of reference include the elimination of having to mentally transform a map representation to match the actual environment (Wickens, 1999) and the capability of obtaining highly detailed information about a specific portion of the battlefield terrain by "zooming in" to that region. Research in the domain of aviation has illustrated the benefits of an egocentric viewpoint in tasks of local guidance (e.g., maintaining a specified flight path or navigation to a specific target) (Wickens, 1997; Olmos, Wickens, & Chudy, 1997; Wickens & Prevett, 1995). Collectively, research has consistently shown better (i.e., faster)

travel to targets or guidance along a given flight path with immersive displays (Wickens & Prevett, 1995; McCormick & Wickens, 1995; McCormick, Wickens, Yeh, & Banks, 1997; Olmos, Wickens, & Chudy, 1997). The egocentric frame of reference presents the environment from a viewpoint that is compatible with the axis of rotation. In addition, the high gain of the egocentric viewpoint provides a corresponding higher gain indication of error, resulting from the translation of a given control input into a larger change in display view (Wickens & Baker, 1995; Wickens, 1995). However, since this technique only presents that information within a relatively limited FFOV, much of the information regarding the surrounding environment is lost. This has been termed a "key hole" view of the environment (Woods, 1984). An exocentric frame of reference, on the other hand, provides the observer with a more complete view of the surrounding environment. Commanders need to be aware of surrounding terrain and the positioning of friendly and enemy troops throughout the battle environment in order to make timely planning decisions. A broad field of view provided by an exocentric frame of reference provides the "big picture" necessary for commanders in battlefield planning tasks.

Few studies exist that examine the issues of immersion in making tactical judgments. Our study can hopefully provide some initial insight into what immersion can offer to the domain of battlefield visualization. We discuss the results that findings from within the aviation domain have shown with respect to the ability to precisely locate targets in the air, their location relative to surfaces, and envisioning terrain.

Location of Targets in the Air

Although perceptual biases in judging the relative location of points in space can occur in both egocentric and exocentric viewpoints, the costs to performance can be worse with the more exocentric viewpoints. One's own location in the environment as well as another object's location must be determined in the exocentric view (Wickens & Baker, 1995). The comparison that McCormick, Wickens, Yeh, and Banks (1997) made of 3D egocentric and exocentric frames of reference for data visualization revealed a substantial cost of the exocentric viewpoint when precise judgments are made regarding the position of targets in 3D space. Participants were instructed to navigate through a database and penetrate flashing target cubes at various locations within the data environment. As participants neared the target cubes, results indicated substantially more maneuvering and subsequently more time spent near the target as participants tried to make contact using the exocentric display format. Determining the precise location of the target cube relative to ownship, which is necessary for successful navigation to and penetration of the cube, was more difficult with the exocentric format because of perceptual ambiguities. Olmos, Wickens, and Chudy (1997) also compared immersed versus non-immersed

views in target location and did not find a distinct advantage for either view in accurately estimating the relative position of intruders.

Location Awareness of Points Relative to Surfaces

When judgments are made concerning the location of objects relative to surfaces, hazards, or surrounding terrain, studies indicated benefits for increasing levels of exocentricity (Barfield & Kim, 1991; Wickens & Prevett, 1995; McCormick, Wickens, Yeh, & Banks, 1997). Wickens and Prevett (1995) examined the effects of varying degrees of exocentricity on pilots' spatial judgments in a simulated landing task and found more accurate performance with increasing levels of exocentricity. At extreme levels of exocentricity, however, accuracy was significantly lower.

Comparing the utility of immersed and non-immersed frames of reference for guidance and tactical awareness, Olmos, Wickens, and Chudy (1997) found a benefit for immersion in avoiding hazard volumes. Results indicated a slight advantage for the split screen display (a combined immersive and global exocentric display) in terms of the amount of time actually spent within a hazard volume. However, other analyses performed by the authors suggested the concerns about a "keyhole effect" caused by the immersed display.

McCormick, Wickens, Yeh, and Banks (1997) compared display formats of varying degrees of exocentricity (immersed, tethered, and exocentric) within the context of database visualization. Performance in judgments requiring participants to determine the location of target cubes in relation to the colored walls or "surfaces" of the environment revealed a benefit to the exocentric display format. Participants were significantly more accurate in their judgments when viewing the exocentric display than when immersed within the database.

An important point to note is that the immersed display format is, by definition, interactive, and it may be the interactivity (i.e., shifting a viewpoint) as much as the immersed view that helps performance. Barsam and Simutis (1984) used both exocentric and immersive display formats to examine the effects of training on performance of military terrain visualization tasks. Enlisted soldiers were either actively or passively trained using a 2D contour map and a 3D immersive terrain display. Actively trained soldiers were permitted to freely explore the 2D terrain map, selecting both a location and directional orientation within the terrain to view in the corresponding immersive display format (essentially shifting their viewpoint). In the passive training conditions, however, the position and direction of viewpoint were randomly generated by the computer. Soldiers were then given a pencil and paper terrain visualization test, involving

landform and ridge or valley identifications, as well as comparisons of map segments to corresponding visualized scenes. Results showed that by permitting soldiers to actively select 3D views and ground profiles to be generated, their performance increased to almost double that of the passively trained soldiers. However, one could also argue that if soldiers were randomly given a sub-optimal viewpoint and they kept it, they would not perform well on the terrain visualization tests, pointing to a possible confound between randomness and passive viewing in the study.

Recognizing (Envisioning) the Shape of the Terrain

Since the ability of a commander to visualize the battlefield environment relies upon an overall understanding of his or her surroundings, it seems natural that a display format that presents more information regarding the surrounding terrain would prove most beneficial. The nature of the exocentric viewpoint is such that it presents a global picture or "God's eye" view of the environment (Wickens, 1995). An egocentric frame of reference, in contrast, displays a limited portion of the environment at a given time, requiring the viewer to cognitively "link" these individual views into a coherent whole. Aretz (1991) found that an egocentric frame of reference inhibited pilots' ability to form a "mental map" of the environment. Likewise, Williams, Hutchinson, and Wickens' (1996) comparison of different training methods' effects on pilots' transfer performance in a navigational task indicated a benefit for the more exocentric display format in developing an understanding of the overall flight environment. The advantages of an exocentric frame of reference for developing this knowledge have also been seen within the context of data visualization. When participants in the study by McCormick, Wickens, Yeh, and Banks (1997) were asked to determine the overall configuration of the databases they had navigated through in order to penetrate various target cubes, their performance was significantly more accurate with the exocentric frame of reference than with the egocentric viewpoint.

Collectively, results show performance trade-offs between display dimensionality and frame of reference, depending upon the specific tasks involved and information demands of the pilot. Table 1 lists these trade-offs for each of the three types of judgments. Estimating the relative position of a point in space is best served by a 2D display (rather than a 3D format) and an egocentric viewpoint. When tasks involve judging the position of targets relative to surfaces, results do not indicate an overall advantage for either a given display format or viewpoint location over another. However, the benefits of a 3D representation and an exocentric viewpoint can readily be seen when the viewer is trying to develop an understanding of the global configuration of terrain or surrounding environment.

Table 1

Performance Trade-offs Between Display Dimensionality and Frame of Reference for Different Judgments

	Point	Surface	Envisioning
Dimensionality	2D	=	3D
Egocentricity	Egocentric	=	Exocentric

Present Research

In summary, the existing aviation literature has shown that the benefits of employing one type of display format instead of another are highly task dependent. However, very little literature exists that directly compares these aspects within the context of battlefield terrain visualization. The present research attempts to bridge that gap by manipulating the display format used to represent the battlefield terrain, the complexity of the terrain, and the types of tasks performed using these different representations. Before the presentation of actual experimental scenarios, participants will be asked to master a small number of "rules" regarding battlefield mobility. They will be given some period of time to study these rules and will then view a series of electronic maps that depict different battlefield situations on both flat and hilly terrain. For each map presented, participants will be asked a series of questions relating to mobility assessment, relative locations of units and or destinations, and LOS visibility. Participants will need to answer these questions by relying upon one of three electronic map display formats: a 2D planar format, with changes in elevation demarcated by contour lines, a 3D perspective format providing an integrated view of the terrain from a stationary, exocentric viewpoint, or a 3D perspective format with a rotating viewpoint. Similar to many of the findings cited in aviation literature, we would expect to find performance trade-offs between display representations, depending upon the task involved. Research findings relevant to the proposed hypotheses of this study are summarized in Table 2.

Relative Position Judgments

The 2D contour map display would seem best suited to tasks that require the determination of relative lateral position of objects within the battlefield. These judgments are constrained to a dimension of the battlefield, the lateral axis, which the 2D contour format unambiguously represents (Tham & Wickens, 1993). Most of the costs associated with the 3D display formats arise because of ambiguities parallel to the viewing axis, making it difficult to decipher changes in the lateral axis from those in the vertical axis (McGreevy & Ellis, 1986;

Gregory, 1977). This often results in a performance decrement with 3D displays in judging the precise location and vector of a single point in space (Merwin & Wickens, 1996; O'Brien & Wickens, 1997; Wickens, Miller, & Tham, 1996; May, Campbell, & Wickens, 1996).

Table 2

Summary of Findings From Aviation Research and Their Relevance to Proposed Hypotheses in the Study of Battlefield Visualization

Research finding	Soldiers' tasks	Experimental judgment type	Predicted display benefit
O'Brien & Wickens (1997) Boyer & Wickens (1994) May, Campbell, & Wickens (1996) Olmos, Wickens, & Chudy (1997) Davenport (1997)	Assessing mobility	"Which do you estimate will be the fastest route for unit A to reach point B?" "Which one of these paths cannot be taken by unit X to reach destination Kilo?" "Which unit will get to destination Bravo first, taking the travel paths shown?"	2D = 3D Exocentric
Merwin, O'Brien, & Wickens (1997) Olmos, Wickens, & Chudy (1997) Wickens, Miller, & Tham (1993) Wickens, Liang, Prevett, & Olmos (1996) Olmos, Liang, & Wickens (1997)	Assessing relative location of friendly and enemy units	"Which unit is located closer to destination Echo?" "As unit C traverses the path shown to Echo, will it be within firing range of unit X?"	2D
Olmos, Wickens, & Chudy (1997) Wickens & Prevett (1995) McCormick, Wickens, Yeh, & Banks (1997)	LOS visibility	"If you are positioned at point C, can you see unit A?" "How long will unit D be visible to the enemy, taking the travel plan shown to destination Alpha?"	2D = 3D Egocentric
Hickox & Wickens (1996) Williams, Hutchinson, & Wickens (1996) Wickens, Merwin, & Lin (1994) McCormick, Wickens, Yeh, & Banks (1997) Wickens & Prevett (1995)	Envisioning terrain		3D Exocentric

Mobility Assessment

The advantages of one display format over another may be less clear when tasks require the assessment of mobility across terrain. According to the proximity compatibility principle (Wickens & Carswell, 1995), tasks that require integration across all three axes, such as determining appropriate travel routes across 3D terrain, would seem best served by a display format that integrates information from all three axes into a single 3D representation. However, previous aviation research has shown that biases of the 3D display often outweigh the benefits provided by information integration when these types of judgments are made (Boyer & Wickens, 1994; May, Campbell, & Wickens, 1996; Olmos, Wickens, & Chudy, 1997; Davenport, 1997).

LOS Visibility

Ray (1994) suggests that in order to support good visibility judgments, the following capabilities should be included in a commander's terrain representation: (a) the comparison of several different locations on the map in an efficient way, (b) comparison of terrain from both friendly and enemy (target) viewpoints, and (c) varying degrees of detail in the representation to support investigation of different tactical locations. These types of battlefield judgments require the ability to determine the relative position of targets to one another (e.g., "I am here and the enemy is over there") as well as the terrain lying between the two targets, which will ultimately determine their visibility to one another. Findings from aviation have shown the lack of a distinct benefit of either the 2D or 3D display format in making judgments regarding the location of objects relative to terrain surfaces or hazards (Boyer & Wickens, 1994; May, Campbell, & Wickens, 1996; Olmos, Wickens, & Chudy, 1997; Davenport, 1997). By incorporating an egocentric frame of reference, however, we would predict a substantial benefit of the 3D display in making LOS judgments. Ambiguity as to the location of units and or intervening terrain when the 3D exocentric display is viewed can be resolved by actually positioning oneself in the exact location and orientation to ascertain what can or cannot be seen from that vantage point (Wickens & Baker, 1995).

METHOD

Participants

Thirty officers (24 males and 6 females) from the United States Military Academy at West Point volunteered to participate in the study. These officers were comprised of 21 Captains, 5 Majors, and 4 Lieutenant Colonels from different branches of the Army. Participants were asked the following questions to better determine their previous map reading experience:

1. How many years' experience do you have reading battlefield terrain maps?

2. How many years' experience do you have maneuvering in the field with battlefield terrain maps?

3. How many years has it been since you last read battlefield terrain maps? and

4. How many years have expired since you last maneuvered in the field with battlefield terrain maps?

The mean number of years of prior experience in reading battlefield maps was 12.9 and ranged from 4 years to 24 years. The mean number of years of prior experience maneuvering in the field with battlefield maps was 9.6 and ranged from 1 year to 24 years. The mean number of years since participants had last read battlefield terrain maps was 1.8 and ranged from less than 1 year to 5 years. Finally, the mean number of years since participants had last maneuvered in the field with battlefield terrain maps was 3.1 and ranged from less than 1 year to 16 years.

Apparatus

The experimental scenarios were run using a Silicon Graphics® (IRIX®) workstation and viewed on a Silicon Graphics® 20-inch color display. Terrain databases used in the experimental scenarios were obtained from the U.S. Geological Survey's collection of 1° (3- by 3-arc-second data spacing) Digital Elevation Model (DEM) data files. Each database DEM file contains approximately 1,200 elevation samples, covering an area 1° of latitude by 1° of longitude, roughly 3,600 square miles. The specific databases used in this study depicted terrain elevations in the following locations: (a) Wichita, Kansas; (b) Dubuque, Iowa; (c) Clovis, New Mexico; (d) Las Vegas, Nevada; (e) Medford, California; and (f) Pueblo, Colorado. This created an equal combination of flat terrain and hilly terrain to be depicted in the experimental displays. Terrain was represented in 200-meter intervals using a color-coding scheme similar to that of Wickens and May (1994). Terrain elevations were mapped to a continuous color scale from pale yellow (lowest elevation) to burnt red (highest elevation), with intermediate colors at equal intervals.

Participants used a combination of key presses and mouse control to change their viewpoint within the terrain displays and used mouse input to elicit responses to the various experimental questions. In order to change their viewpoint, participants were required to specify both a location within the display to which they wished to move and an azimuth angle view (left-right orientation) at that specified location. To select a particular viewpoint location, participants needed to position the mouse cursor on that area and then click the left mouse button to complete

the selection. Choosing a certain orientation at that location was achieved by manipulating left and right arrow keys on the keyboard. A graphic compass, equipped with an arrow marker depicting the current orientation, was located on the left-hand side of the map display for reference. The orientation of this arrow marker changed according to participants' left-right arrow key inputs. Each input corresponded to a 5° change in orientation. Pressing the middle mouse button executed participants' options and presented them with the corresponding "immersed" view of the terrain. Once immersed in the display, participants were able to change the vertical orientation of their viewpoint (to look either up or down) by pressing the up-down arrow keys on the keyboard, respectively. Each up-down arrow key input corresponded to a 10° change in orientation. Pressing the right mouse button allowed participants to "zoom out" of the terrain and return to the initial exocentric viewpoint. This particular procedure was implemented so as not to require continuous updating of complex 3D terrain imagery as the participants rapidly moved their viewpoint across it and rotated around it. Terrain lighting and shading were also provided in the 3D displays of both hilly and flatter terrain. Toggling between this viewing option and color-coded contour intervals was achieved by pressing the "L" key on the keyboard.

Participants were able to elicit responses to each of the judgment questions by pointing the mouse cursor to the appropriate response in the question box and clicking the left mouse button to select that response.

Tasks and Scenarios

Before the presentation of actual experimental scenarios, participants were asked to master a small number of "rules" regarding battlefield mobility (see Appendix A). They were given a 24-hour period to study these rules and then viewed a series of electronic maps that depicted different battlefield situations on both flat and hilly terrain. For each map presented, participants were asked a series of questions, requiring them to make various judgments about the units presented in the display, while taking into account both the depicted terrain and the pre-defined mobility rules. The experimental questions were designed to address participants' capability of making three distinct types of battlefield judgments: (a) determining relative distance (between two units, a unit and a given destination, etc.), (b) assessing mobility through terrain, and (c) determining LOS. Examples of these questions include the following:

1. As Unit X traverses the path to point Alpha, will it be within firing range of enemy unit Y (relative distance)?

2. Which do you estimate will be the fastest route for unit X to reach point B (mobility assessment)?

3. If you are positioned at point B on the map, can you see enemy unit Y (LOS)?

Participants' goals were to respond to these questions both as rapidly and accurately as possible by relying upon one of the three electronic display formats: 2D contour, 3D perspective, or 3D interactive. Participants were also required to supply a verbal rating of their certainty in having responded to the question accurately. This rating could vary from the following responses: "certain," "moderately certain," or "uncertain."

Electronic Map Display Formats

Each electronic map display covered an area of terrain approximately 8 kilometers by 6.5 kilometers and included roads, rivers, small towns, friendly and enemy units, and travel routes leading through or to specified destination points. Roads were represented as black lines, rivers as blue lines, and small towns as a cluster of red boxes or "buildings." Friendly and enemy units were rendered as purple boxes, while destinations and location points appeared as small red circles. Travel routes were rendered as red lines, leading from one unit or destination to another. Alpha-numeric labels, corresponding to the various components in a given battlefield scenario, also appeared on the displays. Experimental questions appeared in the upper left-hand corner of each of the three display formats.

2D Planar Format

Figures 3 and 4 present the 2D display formats used by participants in the experiment. Figure 3 depicts relatively flat terrain, and Figure 4 shows mountainous terrain. The 2D map display provided participants with a top-down view of the terrain, demarcated by color-coded contour intervals every 200 meters in elevation. Contour lines, delineating 40-meter changes in elevation, were provided for those maps in which the elevation of the entire area of flatter terrain was depicted within a single color interval (see Figure 3). Small, black "x's" appeared along with the contour lines to designate points of highest elevation in the display. A scale marker was displayed in the lower left corner of each 2D map display. Approximately 1 inch long, it represented a 1-kilometer distance on the map and was useful in making distance estimations.

3D Perspective Format

An example of the 3D perspective format is shown in Figure 5. The perspective display presented the terrain from a static, exocentric viewpoint at an elevation angle of 45°. The scale marker used to represent a 1-kilometer distance on the map appeared in the middle, right-

hand side of every perspective map display. Figure 6 depicts the same area of terrain as in Figure 5 as it would have appeared when the terrain lighting and the shading option were executed.

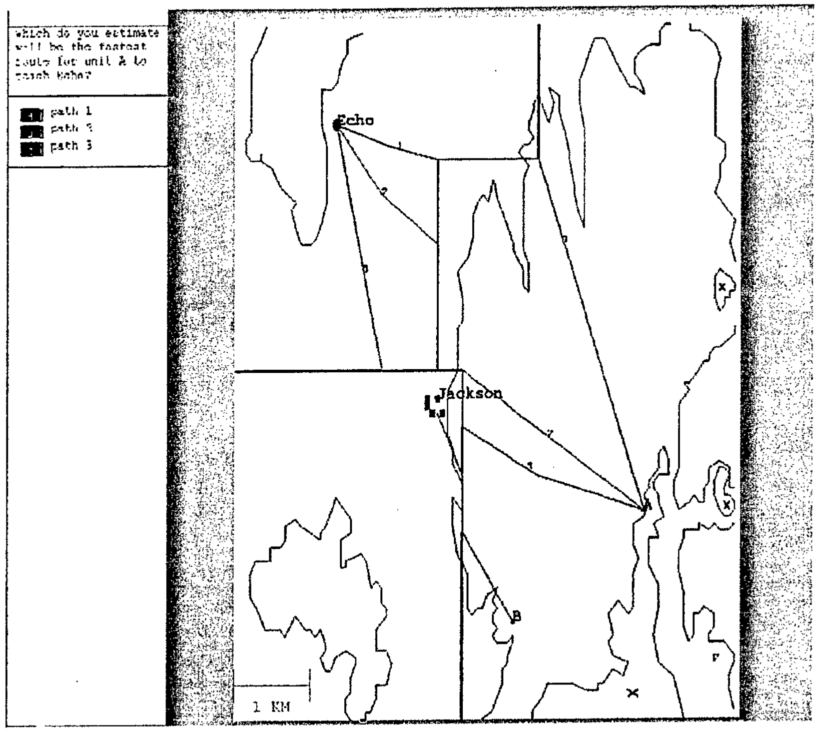

Figure 3. Two-dimensional contour map display (flat terrain).

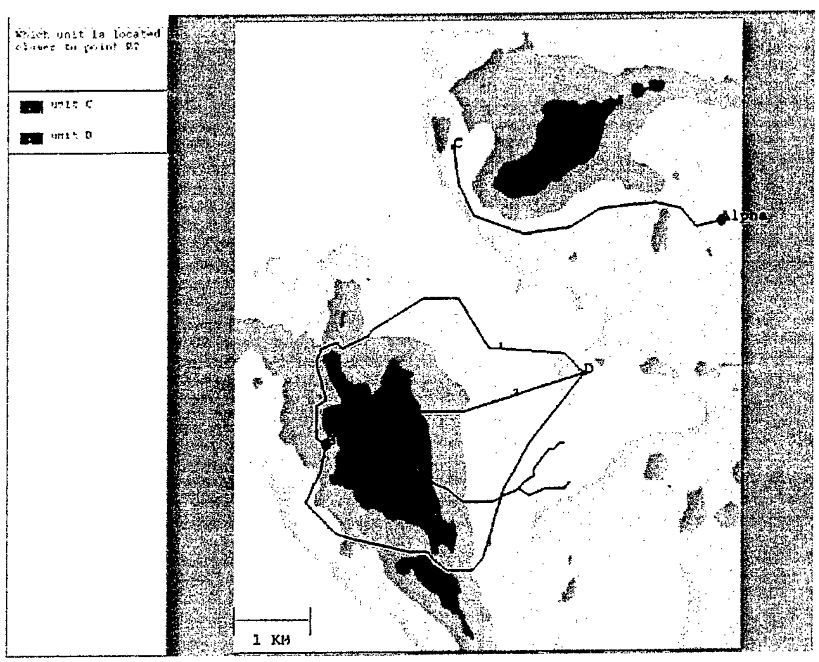

Figure 4. Two-dimensional contour map display (hilly terrain).

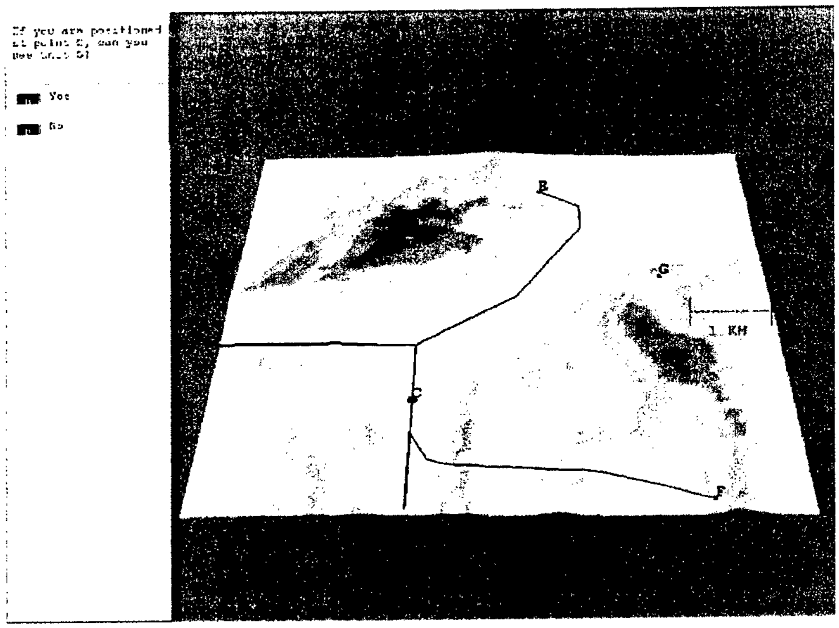

Figure 5. Three-dimensional static perspective map display.

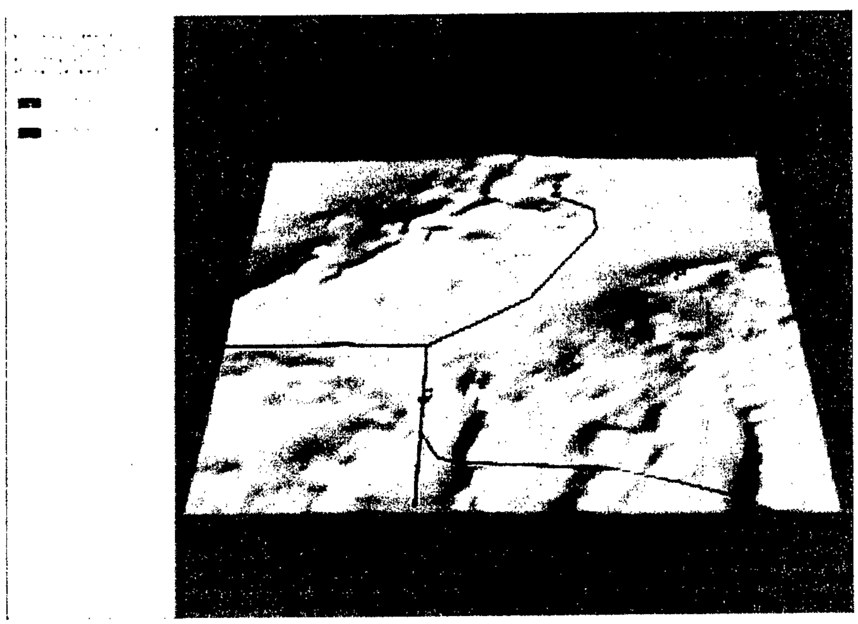

Figure 6. Three-dimensional static perspective map display with terrain lighting.

3D Interactive Format

The interactive display initially provided participants with a view of the terrain from the same exocentric viewpoint as the perspective format shown in Figures 5 and 6. An example of the 3D interactive display format is shown in Figure 7. As participants selected an area of terrain to "zoom in" on, a small red circle appeared on the display to mark the specified location. The participants' current viewpoint orientation was depicted by the graphic compass located in the middle, left-hand side of the display. Changes in the current viewpoint orientation were reflected by corresponding changes in the compass needle's orientation. Figure 8 presents the resulting "immersed" display of terrain that would correspond to a participant's selected viewpoint location and orientation. Participants also had the capability of viewing both the exocentric and immersed display formats with either color-coded contour intervals or with terrain lighting and shading.

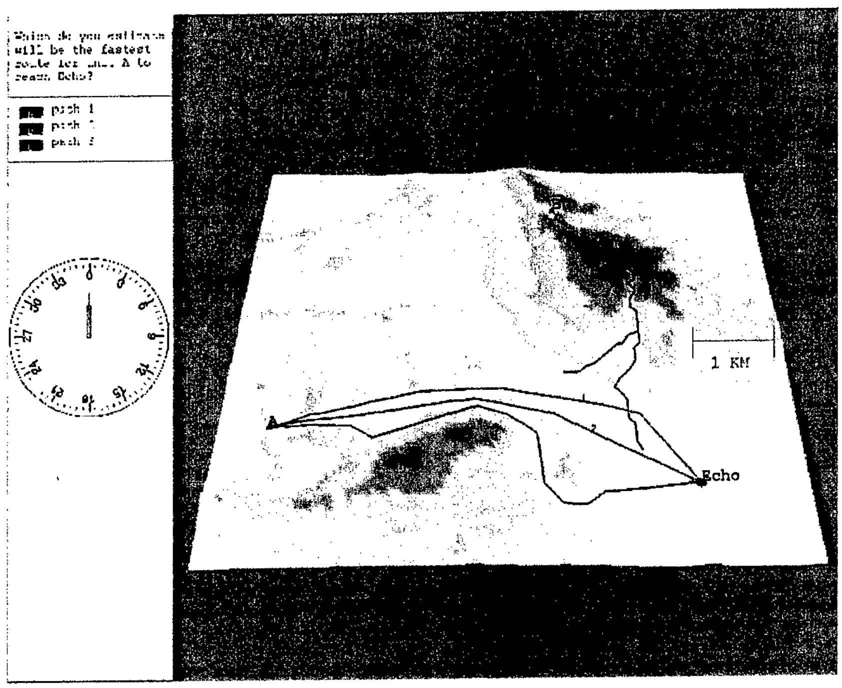

Figure 7. Three-dimensional interactive map display.

Design and Procedure

The experiment used a 3 x 3 x 2 factorial, within-subjects design. All participants were exposed to each of the three display types (2D, 3D perspective, and 3D interactive), each of the three different battlefield question types (relative distance, mobility assessment, and LOS judgments), and both hilly and flat terrain. Participants were assigned to one of six possible groups, shown in Table 3, which were defined by the ordering of display type presentation (D1-

D3) and database presentation (DB1-DB6). Display ordering was counterbalanced across groups. The ordering of the six different terrain databases (DB1-DB6) was also counterbalanced across groups and allowed for both flat (F) and hilly (H) terrain to appear within a given display type. The order of presentation of the three battlefield questions was counterbalanced within a given terrain database.

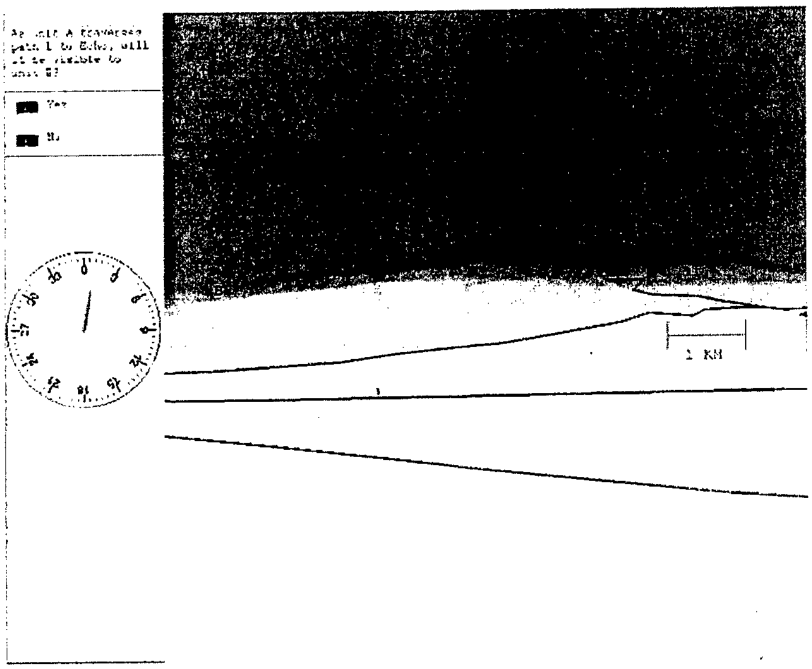

Figure 8. Immersed view of three-dimensional interactive map display.

Table 3

Experimental Design Used in the Battlefield Visualization Study

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
D 1: DB1 (F)	D 1: DB6 (H)	D 3: DB1 (F)	D 3: DB6 (H)	D 2: DB1 (F)	D 2: DB6 (H)
D 1: DB2 (H)	D 1: DB5 (F)	D 3: DB2 (H)	D 3: DB5 (F)	D 2: DB2 (H)	D 2: DB5 (F)
D 2: DB3 (H)	D 2: DB4 (F)	D 1: DB3 (H)	D 1: DB4 (F)	D 3: DB3 (H)	D 3: DB4 (F)
D 2: DB4 (F)	D 2: DB3 (H)	D 1: DB4 (F)	D 1: DB3 (H)	D 3: DB4 (F)	D 3: DB3 (H)
D 3 : DB5 (F)	D 3 : DB2 (H)	D 2: DB5 (F)	D 2: DB2 (H)	D 1: DB5 (F)	D 1: DB2 (H)
D 3: DB6 (H)	D 3: DB1(F)	D 2: DB6 (H)	D 2: DB1 (F)	D 1: DB6 (H)	D 1: DB1 (F)

The entire experiment was completed in a single session, lasting approximately 2 hours. The day before being scheduled to run in the study, participants were given a written description

of the background of the study, overview of experimental tasks, and a list of mobility rules, shown in Appendix A, with which to familiarize themselves. On the day of the actual experimental session, participants were first given a timed Mental Rotation Test (Peters, 1995), based upon Vandenberg and Kuse's (1978) Mental Rotation Test Forms MRT-A to MRT-D. Before beginning the test, participants received a full explanation of test procedures and a total of 5 minutes to work through a series of practice problems. The actual test consisted of 24 items, which were divided into two-problem sets. Participants were given 3 minutes to complete each problem set, with a short break in between sets.

After completing the Mental Rotation Test, participants re-read the "Commanders' Display of Terrain Information: Battlefield Planning Simulation-Battlefield Planning Displays" experimental instructions that had been given to them the day before, asking the experimenter to clarify any aspects that seemed unclear. Participants were then presented with 18 practice trials, consisting of three questions in each of the three display formats with both flat and hilly terrain, in order to familiarize themselves with the experiment. Participants completed a total of 72 experimental trials. Of those 72 trials, 24 were completed in each of the three display conditions. Within each grouping of 24 trials, participants completed half (12) the trials with a display depicting flat terrain and half (12) depicting hilly terrain. Within each set of 12, 3 trials were presented with the world oriented in each of the four cardinal directions. Each trial consisted of the subject being asked one of each of the three types of battlefield judgment questions. As participants responded to each question, they supplied the experimenter with a verbal rating of their confidence in having responded to the question accurately. Upon completion of all experimental trials, participants were debriefed, asked for any additional comments, and thanked for their participation.

Performance Measures

Various performance measures were recorded in an effort to quantify aspects of officers' battlefield planning performance with electronic map displays. These measures included battlefield judgment performance, spatial ability, and the use of 3D display capabilities.

Battlefield Judgment Performance

Response accuracy and latency were assessed for each of the three type battlefield judgment questions. Participants' confidence ratings were also recorded in an effort to better quantify those particular battlefield judgments that may be more difficult to make with certain electronic map display formats.

Spatial Ability

Many battlefield planning tasks are inherently spatial in nature. This often requires mental rotation of static, exocentric battlefield maps in order to visualize 3D terrain features. Research has shown performance benefits in pencil-and-paper terrain visualization tasks with increasing levels of spatial ability (Barsam & Simutis, 1984). Peters' (1995) revision of Vandenberg and Kuse's (1978) Mental Rotation Test Forms MRT-A to MRT-D was used to measure participants' spatial ability. This score was taken in an effort to further understand performance differences in battlefield planning that may arise from individual differences in spatial ability and their interplay with different formats of map display technology on task performance.

Use of 3D Display Capabilities

Several different measures were taken in order to better quantify participants' use of interactivity in the 3D display for battlefield planning. The number of times participants executed the terrain lighting option was measured in both the static and interactive 3D display formats. The number of movements participants made in the 3D interactive display when positioning themselves in various locations within the terrain was also recorded. These movements included selecting a position on a display, "zooming in" to the egocentric display view, "zooming out" to the exocentric display view, as well as moving viewpoint orientation vertically in both directions and horizontally in both directions. Also measured was the length of time participants spent in the egocentric view and the time they spent in the exocentric view when viewing and maneuvering in the 3D interactive display.

RESULTS

The data were analyzed using the Statistical Analysis Software (SAS®) package. Before data analysis, the distributions of the dependent variables were examined for extreme values. Data points that exceeded three standard deviations from the mean of the distribution to which they belonged were classified as outliers and were excluded from analysis. This resulted in the exclusion of 45 cases of 2,160 (roughly 2%) data points.

Analysis of the experiment was conducted using a repeated measures analysis of variance (ANOVA) across the three display formats (2D planar, 3D perspective, and 3D interactive), three judgment types (distance, mobility, and LOS), and two levels of terrain (flat and hilly). The combination of the ordering of terrain database and ordering of display format created the

between-subjects factor of "group." Analysis did not reveal a significant effect of subject grouping on either response time to the three judgments, $F(5,24) = 1.86, p > .14$, or combined accuracy and certainty rating (performance index) of the judgments, $F(5,24) = .48, p > .78$. Also of interest was a possible interaction between display type and order of presentation, signifying the presence of some asymmetrical transfer. Analysis did not show the Display Types x Order of Presentation interaction to be significant, $F(4,54) = 1.69, p > .17$.

Judgment Performance

In order to obtain a finer measure of participants' performance in making the experimental judgments, judgment accuracy was combined with participants' verbal confidence ratings (of their having responded accurately to the question). This created a performance index, shown in Table 4, which ranged in value from 0 to 5. Accuracy was scored either as incorrect or correct. Certainty was classified as certain, moderately certain, or uncertain. For example, a correct answer of moderate certainty would be scored as a "4."

Table 4

Performance Index Ratings Used in Data Analysis

Participants' certainty ratings	Answer "Correct"	"Incorrect"
"certain"	5	0
"moderately certain"	4	1
"uncertain"	3	2

Figure 9 shows mean performance score as a function of both display format and judgment type. A repeated measures ANOVA revealed a significant main effect of display format on judgment performance, $F(2,58) = 8.83, p < .01$. The 2D display format resulted in the highest average performance of judgments. Contrasts revealed significantly better performance in the 2D display format than in both the 3D perspective and 3D interactive formats, $F(1,29) = 19.41, p < .01$ and $F(1,29) = 5.02, p < .03$, respectively. Contrasts also revealed a non-significant trend toward higher performance with the 3D interactive display in comparison to the 3D perspective display format, $F(1,29) = 3.23, p > .08$.

A main effect of judgment type on performance was also found to be significant, $F(2,58) = 10.27, p < .0002$. Significantly higher performance was found with LOS judgments than with mobility judgments and distance judgments, $F(1,29) = 14.49, p < .01$ and $F(1,29) = 20.70, p < .01$, respectively. Average performance of mobility judgments was virtually equal to that of distance judgments ($F(1,29) = 0, p = 1.0$).

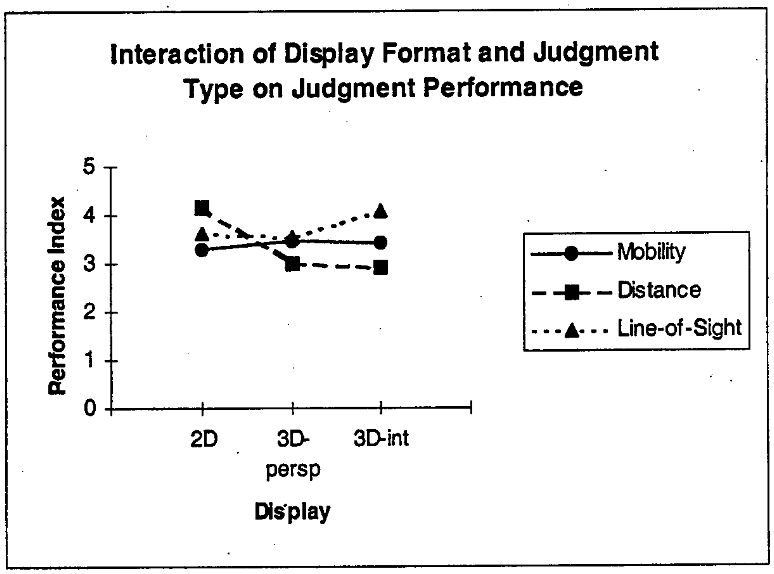

Figure 9. Display Format x Judgment Type interaction on judgment performance.

Most importantly, as shown in Figure 9, analysis revealed a significant Display Format x Judgment Type interaction on judgment performance, $F(4,116)=18.78, p < .01$. Performance when making distance judgments was best with the 2D display, while performance of LOS judgments was best served by the 3D interactive display. Performance when making mobility judgments was just about equally supported by each of the three formats.

Terrain Development

Analysis revealed a significant effect of terrain type on judgment performance. Participants' judgment performance was significantly better when viewing flat terrain than when viewing hilly terrain, $F(1,29) = 6.71, p < .01$. Display format did not interact with terrain type to affect judgment performance, $F(2,58) = 1.19, p > .31$; however, there was a significant Judgment Type x Terrain Type interaction on judgment performance, $F(2,58) = 10.04, p < .01$. Mean performance of distance judgments as well as LOS judgments remained virtually constant, regardless of the type of terrain viewed. However, mean performance of mobility judgments was

higher when participants were viewing flatter terrain than more mountainous terrain. This finding was expected because, in flat terrain, mobility judgments are simpler, depending solely on factors such as river crossings, whereas in mountainous terrain, such judgments require slope estimation. Analysis did not reveal a significant three-way interaction of display format, judgment type, and terrain type on judgment performance, $F(4,116) = .44, p > .77$.

Response Time

Figure 10 depicts average response time as a function of display format and judgment type. Analysis showed a significant main effect of display format on response time $F(2,58) = 40.61$ $p < .01$. Contrasts revealed significantly faster response times with both the 2D and 3D perspective displays as compared to the 3D interactive display, $F(1,29) = 64.79$ $p < .01$ and $F(1,29) = 40.25, p < .01$, respectively. There was no significant difference in average response times between the 2D display and the 3D perspective displays, $F(1,29) = 2.71, p > .11$.

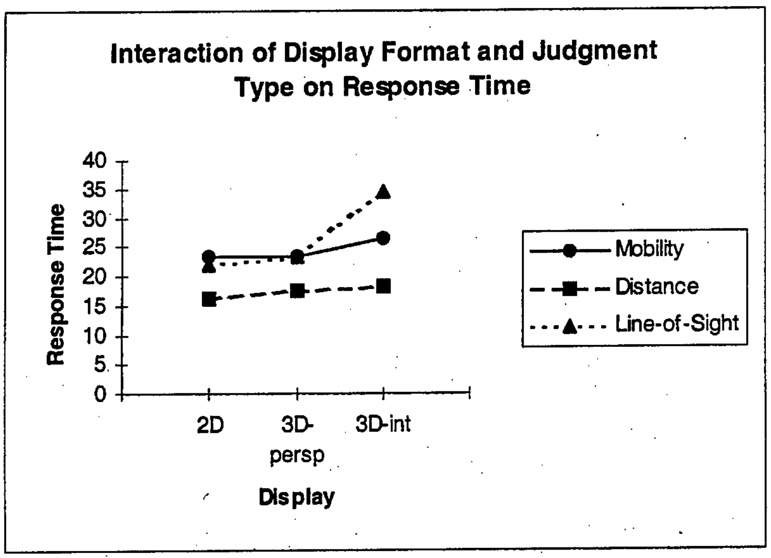

Figure 10. Display Format x Judgment Type interaction on average judgment response time.

Analysis also showed a significant main effect of judgment type on response time $F(2,58) = 86.61, p < .01$. Contrasts revealed significantly faster response times when distance judgments were made than when either mobility judgments, $F(1,29) = 85.93, p < .01$, or LOS judgments, $F(1,29) = 174.36, p < .01$ were made. Contrasts also revealed significantly faster response times when mobility judgments were made than when LOS judgments were made,

$F(1,29) = 9.36, p < .01$. As shown in Figure 10, this effect was particular to the 3D interactive display, as supported by the significant Display Format x Judgment Type interaction on response time, $F(4,116) = 30.14, p < .01$. When viewing the 3D interactive display, participants took longer to respond to LOS judgments than either distance or mobility judgments. However, LOS judgment response times approached those of mobility judgments when subjects viewed the 3D perspective display and were slightly shorter than mobility judgments when subjects viewed the 2D display format.

Comparing Figures 9 and 10, we see that the superior accuracy for the 2D display on distance judgments was not the result of a speed-accuracy trade-off. Participants were both faster and more accurate. However, such a trade-off was reflected in the LOS judgments. The superior accuracy of the interactive display was procured at the cost of the greater response time required for the interactivity.

Terrain Development

The type of terrain (flat or hilly) did not have a significant effect on response time of judgments, $F(1,29) = 0.50, p > .48$. Likewise, the Display Format x Terrain Type interaction did not significantly affect judgment response time, $F(2,58) = 0.22, p > .80$. However, analysis revealed a significant Judgment Type x Terrain Type interaction on judgment response time, $F(2,58) = 11.16, p < .01$. Participants had slightly faster response times on both distance and LOS judgments when viewing hilly terrain. When making mobility judgments, however, participants had faster average response times than when they viewed flat terrain.

Analysis did not reveal a significant three-way interaction of display format, judgment type, and terrain type on average judgment response time, $F(4,116) = 1.14, p > .34$.

Secondary Analyses

Results from the primary analyses of the effects of display format, judgment type, and terrain type on judgment performance and response time raised two additional issues that were addressed through secondary analyses. First, when participants' judgment performance declined as a function of one or more of the independent variables, is that decline attributed to a decrease in accuracy, a decrease in confidence in correct responses, or both? Second, within LOS judgments, participants were asked to make two fundamentally different judgments: (a) assess LOS visibility from a point and (b) assess the visibility of a path. It was hypothesized that

these two judgments may result in differences in judgment response time and performance. Each of these secondary analyses is discussed next.

Judgment Accuracy and Confidence Ratings

Figure 11 depicts participants' mean accuracy of judgments as a function of the display format viewed and judgment type that parallels in form the trend shown in Figure 9. Secondary analysis showed a significant main effect of display type on judgment accuracy, $F(2,58) = 7.32, p < .01$. Participants were significantly more accurate when making judgments with the 2D display than with making either the 3D perspective display ($F(1,29) = 12.45$, $p < .01$) or the 3D interactive display ($F(1,29) = 8.55, p < .01$). There was no significant difference in judgment accuracy between the 3D perspective and 3D interactive displays ($F(1,29) = .16, p > .69$).

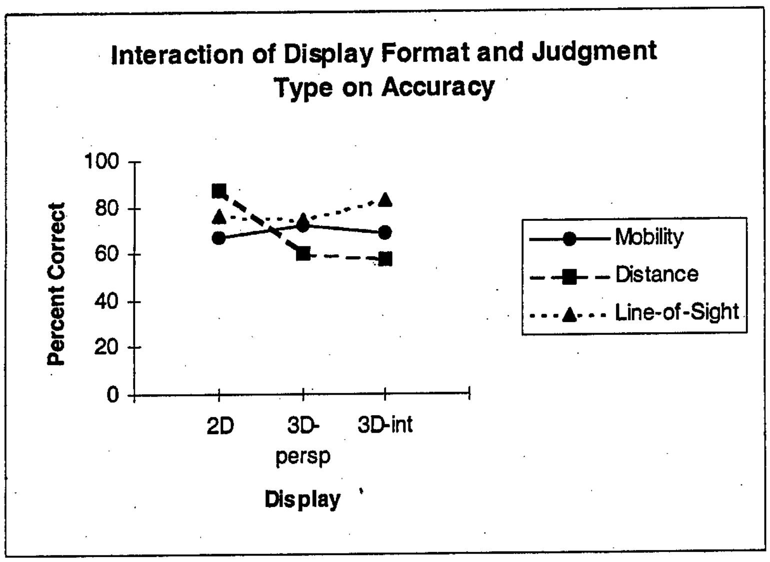

Figure 11. Display Format x Judgment Type interaction on average judgment accuracy.

Results also indicated a significant main effect of judgment type on judgment accuracy, $F(2,58) = 11.80, p < .01$. Participants were significantly more accurate when making LOS judgments than making either distance judgments ($F(1,29) = 22.70, p < .01$) or mobility judgments ($F(1,29) = 14.95, p < .01$). There was no significant difference in accuracy between distance judgments and mobility judgments, $F(1,29) = .18, p > .67$.

There was a significant Display Format x Judgment Type interaction on judgment accuracy, $F(4, 116) = 16.47, p < .01$, consistent with those results found when looking at

judgment performance index shown in Figure 9. Accuracy when making distance judgments was highest with the 2D display, while accurate performance of LOS judgments was best supported by the 3D interactive display. There was a slight benefit in accuracy when mobility judgments were made within the 3D perspective display.

Analyses were also performed to examine the effects of display format and judgment type on participants' confidence ratings. Mean confidence ratings are depicted in Figure 12. Results showed a significant effect of display format on confidence ratings, $F(2,58) = 6.35, p < .01$, with participants giving higher confidence ratings when viewing the 3D interactive display than viewing either the 2D format, ($F(1,29) = 7.63, p < .01$) or the 3D perspective display ($F(1,29) = 0.79$, $p < .01$). There was no significant difference in ratings between the 2D and 3D perspective displays.

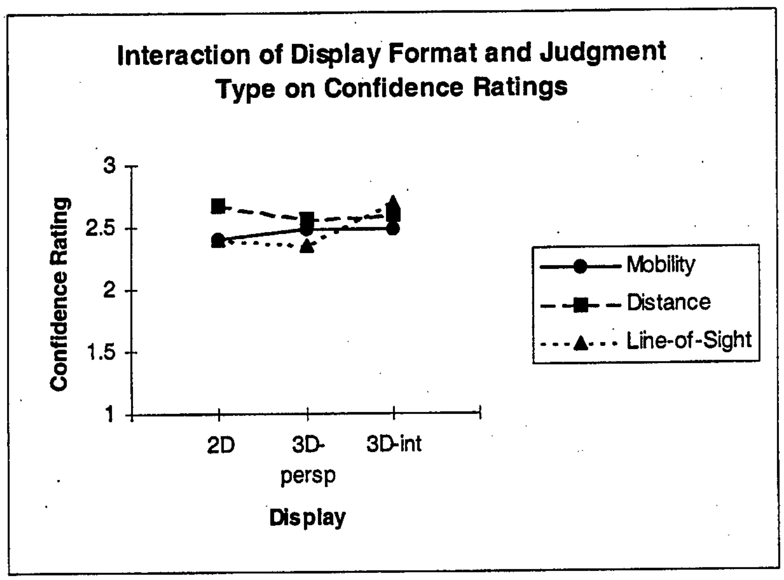

Figure 12. Display Format x Judgment Type interaction on participants' confidence ratings.

Judgment type also had a significant effect on participants' confidence ratings, $F(2,58) = 8.36, p < .01$, with participants giving higher confidence ratings when making distance judgments than making either mobility judgments ($F(1,29) = 14.58, p < .01$) or LOS judgments ($F(1,29) = 12.76, p < .01$. Participants did not give significantly different confidence ratings when making mobility or LOS judgments.

There was a significant Display Format x Judgment Type interaction on participants' confidence ratings, $F(4, 116) = 9.96, p < .001$. However, this pattern of results is somewhat different from that found when looking at judgment accuracy as a function of display format and

judgment type (see Figure 11). In that analysis, a dominant source of the interaction was the decrease in accuracy for the two 3D displays on distance judgments. However, in the current analysis, there was no corresponding decrease in confidence, but there was a greater increase in confidence with the interactive displays for LOS judgments.

LOS Judgments

Also of interest in the secondary analyses were any possible performance differences arising from the two types of LOS judgments: visibility from a point and visibility of a path. LOS questions were categorized according to these two groupings, and a repeated measures ANOVA was performed on judgment response time and judgment performance (combined accuracy and participant confidence ratings). Results showed a significant main effect of judgment type on judgment response time, $F(1,29) = 341.81, p < .01$, with participants taking significantly longer to respond to judgments regarding visibility of a path than judgments about visibility from a point. There was a marginally significant Judgment Type x Display Format interaction on participants' response time, with an enhanced disadvantage for the interactive display when path questions were answered, ($F(2,58) = 2.91, p > 0.07$). This resulted because path judgments required moving the viewpoint to different locations (a time-consuming operation), whereas point judgments did not. There was no significant interaction of judgment type with terrain type, ($F(1,29) = 1.46, p > 0.23$).

In addition to taking significantly longer to respond to judgments regarding visibility of a path, participants' judgment performance was significantly lower ($F(1,29) = 66.93$, $p < .01$). Neither the Judgment Type x Display Format interaction ($F(2,58) = .73, p > 0.48$) nor the Judgment Type x Terrain Type interaction ($F(1,29) = .05; p > 0.83$) significantly affected judgment performance.

Display Functionality

Participants were given two different interactive tools to use during the experimental session. These consisted of a terrain lighting and shading functionality and an "immersive" functionality, essentially allowing participants to change their viewpoint location and orientation within the electronic display. Terrain lighting and shading were provided for the 3D static perspective display and the 3D interactive display. The capability of changing one's viewpoint location and orientation was provided exclusively in the 3D interactive display format. Through analyses, we hoped to answer questions regarding the interactive tools: how and when did participants use them, and how was their performance affected?

Terrain Lighting and Shading

Frequencies of terrain lighting and shading key presses as a function of display format and judgment type are shown in Figure 13. The chi-square test statistic was used to test the null hypothesis that terrain lighting and shading were used with equal frequency in both 3D displays, ($X^2_{1,717} = 181.41, p < .01$). Results indicated a main effect of display format, in that participants used terrain lighting and shading significantly more in the 3D perspective display format than in the 3D interactive display.

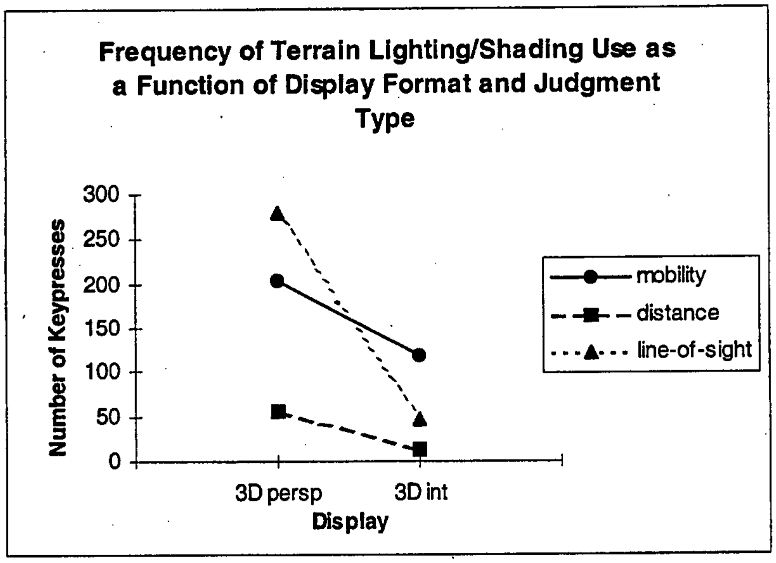

Figure 13. The effects of display format and judgment type on frequency of terrain lighting and shading use.

Likewise, analysis revealed a significant main effect (i.e., non-equal frequencies) of judgment type on the frequency of terrain lighting and shading use, ($X^2_{2,717} = 181.41, p < .01$). Participants used terrain lighting and shading with significantly less frequency when making distance judgments than when making either mobility or LOS judgments, ($X^2_{1,391} = 163.71$, $p < .01$) and ($X^2_{1,395} = 167.21, p < .01$), respectively. Participants' terrain lighting and shading usage was essentially equal when making either mobility or LOS judgments.

The type of judgment appeared to differentially affect the frequency with which participants used the terrain lighting functionality, depending upon display format, (i.e., non-equal frequency across the six cells defined by judgment x display type), ($X^2_{2,717} = 46.77$, $p < .01$). As shown by the pronounced cross-over pattern in Figure 13, the frequency with which participants used the terrain lighting feature decreased substantially more when they were making LOS judgments than when making other judgments within the 3D interactive display

format. A possible explanation for this large decrease could be attributed to the availability of additional interactive tools in the 3D interactive display, as discussed in the section entitled "Control Activity."

Terrain Development

Figure 14 presents the frequency of terrain lighting and shading key presses as a function of judgment type and terrain type. Analysis revealed that participants used the lighting and shading functionality with greater frequency when viewing more mountainous terrain, ($X^2_{1,717} = 93.55, p < .01$).

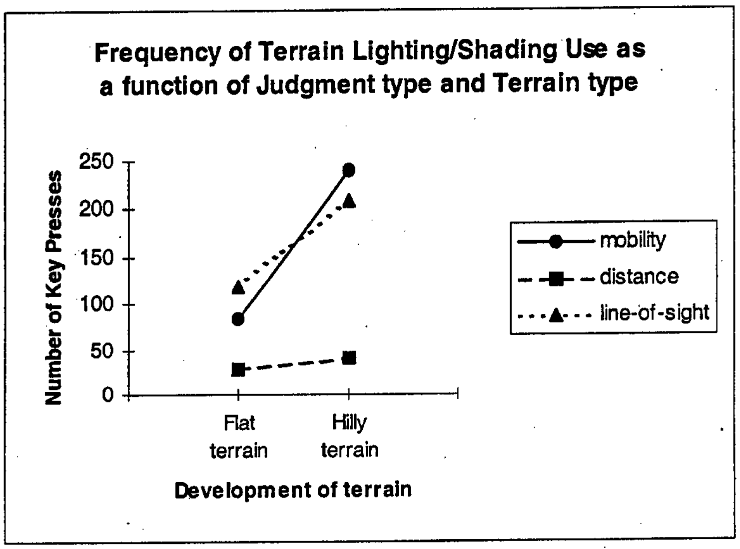

Figure 14. The effects of judgment type and terrain type on frequency of terrain lighting and shading use.

Display format did not appear to have a different effect, depending upon the type of terrain viewed, on the frequency of terrain lighting and shading use ($X^2_{1,717} = .04$, $p > .83$). However, judgment type did differentially affect the frequency with which participants used the terrain lighting and shading functionality, depending upon the type of terrain viewed, (i.e., non-equal frequency across the six cells defined by judgment x terrain type), ($X^2_{2,717} = 10.71$, $p < .01$). Participants used the lighting and shading functionality with greater frequency when making mobility and LOS judgments within more hilly terrain. When making distance judgments, however, participants used the terrain lighting and shading functionality a more or less equivalent amount, across terrain type.

Note that the chi-squared tests performed on the data in Figure 14 do not distinguish questions about which lighting was used from subjects who used the lighting. This

distinction will be addressed more directly as we examine individual differences in performance in the section entitled, "Individual Differences in Display Usage and Effects on Performance."

Control Activity

Within the 3D interactive display exclusively, participants had the capability of changing both their viewpoint location and orientation as they felt necessary to help in making the different experimental judgments. This involved maneuvers such as selecting a location on the terrain, selecting a specific heading (left-right orientation) at that location, "zooming in" to the specified location, changing left-right orientation once positioned at that location, changing up-down orientation, and "zooming out" to the original, exocentric view of the terrain. These individual maneuvers were recorded and analyzed collectively as a measure of "control activity."

The frequency of maneuvering as a function of judgment type and terrain type is shown in Figure 15. The chi-square test statistic was used to test the null hypothesis that participants maneuvered with equal frequency when making all three judgment types. Analysis revealed a significant main effect of judgment type on the amount of participants' control activity, ($X^2_{2,7659} = 6766.53, p < .01$). Participants maneuvered more frequently when making LOS judgments than when making either mobility judgments, ($X^2_{1,7193} = 2986.68, p < .01$) or distance judgments, ($X^2_{1,6380} = 4652.15, p < .01$). In addition, the frequency with which participants maneuvered when making mobility judgments was greater than when making distance judgments, ($X^2_{1,1745} = 378.78, p < .01$). Analysis also revealed that participants maneuvered more in hilly terrain than in flatter terrain, ($X^2_{1,7659} = 252.62, p < .01$).

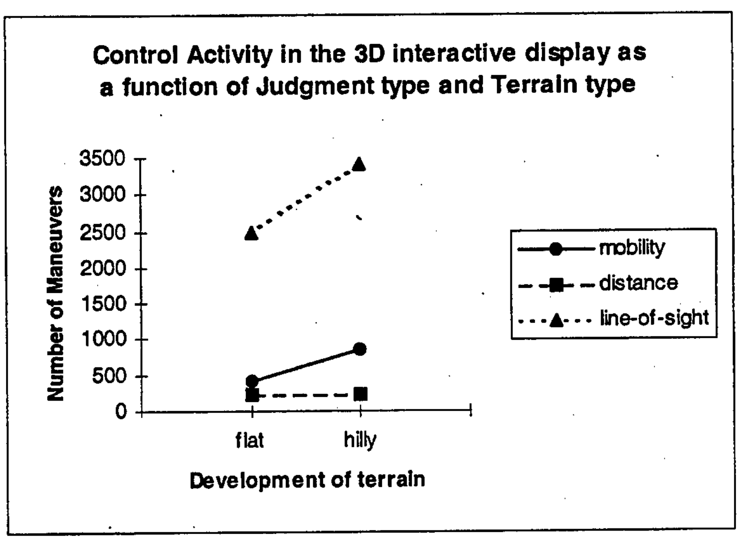

Figure 15. Judgment Type x Terrain Type interaction on the amount of control activity in 3D interactive display.

Judgment type appeared to have a different effect on control activity, depending upon type of terrain, ($X^2_{2,7659} = 52.09, p < .01$). Both mobility and LOS questions induced more control activity in more hilly terrain, whereas distance questions did not.

Amount of Time Spent in Exocentric and Egocentric Views

Analysis was performed within the 3D interactive display on both the amount of time spent in the exocentric view and time spent in the egocentric view, as a function of judgment type and terrain type. Figures 16 and 17 show the amount of time spent in both exocentric and egocentric views for each of the three judgment types in hilly and flat terrain, respectively. Both figures reveal that participants spent a greater proportion of time in the exocentric view than in the egocentric view when making battlefield judgments.

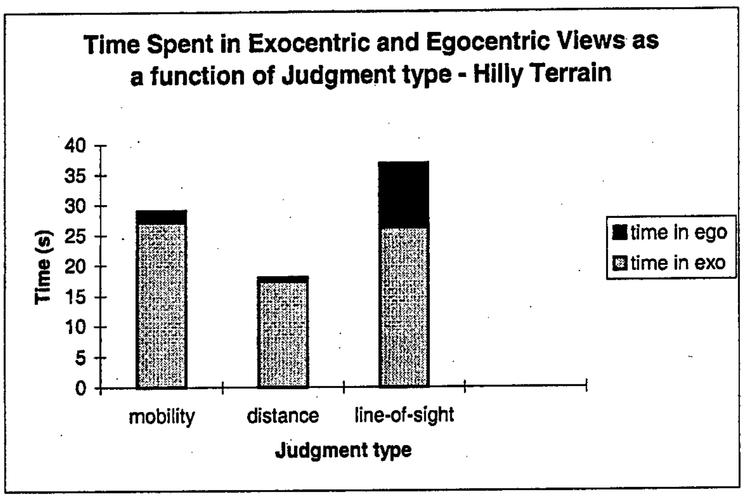

Figure 16. Amount of time spent in exocentric and egocentric views in hilly terrain.

Analysis showed a significant main effect of judgment type on time spent in exocentric view, $F(2,58) = 44.71, p < .0001$. Participants spent significantly less time in the exocentric view for distance judgments than for mobility judgments ($F(1,29) = 47.12, p < .0001$) or LOS judgments ($F(1,29) = 79.61, p < .0001$). Contrasts did not reveal significant differences in time spent in the exocentric view between mobility judgments and LOS judgments, $F(1,29) = 2.46$, $p > .13$. Likewise, analysis of time spent in the egocentric view revealed a significant main effect of judgment type ($F(2,58) = 64.57, p < .0001$), with participants also spending less time in the immersed view for distance judgments than for mobility judgments, $F(1,29) = 5.64, p < .02$, or LOS judgments, $F(1,29) = 77.70, p < .0001$. However, while participants spent the same amount of time in the exocentric view, whether answering LOS or mobility questions, they spent much more

time in the immersed view when making LOS judgments than when making mobility judgments, $F(1,29) = 61.39, p < .0001$.

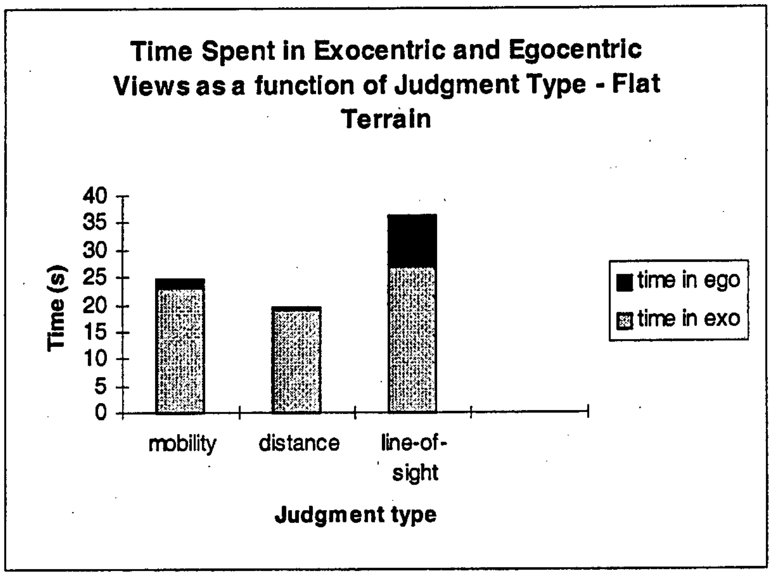

Figure 17. Amount of time spent in exocentric and egocentric views in flat terrain.

Terrain Development

Analysis did not reveal significant differences in the amount of time spent in either the exocentric view, ($F(1,29) = 0.24, p > .63$), or egocentric view, ($F(1,29) = 2.04$, $p > .16$), as a function of the type of terrain (hilly or flat) viewed. In addition, the combination of terrain type and judgment type did not have a significant effect on the amount of time participants spent in the egocentric view, $F(2,58) = .40, p > .67$. Comparing Figures 16 and 17, it can be seen that regardless of terrain type, participants spent more time in the egocentric view when making LOS judgments than when making either mobility or distance judgments. However, analysis did reveal a significant Terrain Type x Judgment Type interaction on the amount of time participants spent in the exocentric view, $F(2,58) = 5.71, p < .005$. As vertical development of the terrain increased, participants spent increasingly more time in the exocentric view when making mobility judgments, surpassing that of LOS judgments.

Individual Differences in Display Usage and Effects on Performance

Participants showed individual differences in the extent of their use of terrain lighting and shading functionality, use of 3D interactive capabilities, as well as differences in spatial ability (Mental Rotation Test scores) and performance scores (combined accuracy and confidence ratings).

In order to investigate relationships between participants' usage of display functionality and their performance, means for all dependent variables of interest were calculated for each of the 30 participants across all display formats, terrain types, and judgment types, as well as within specific combinations of these variables described next. Means were calculated for the following dependent measures: judgment performance, judgment response time, Mental Rotation Test score, frequency of terrain lighting and shading use, and control activity (number of maneuvers).

Collapsed Across All Conditions

Figure 18 plots participants' mean performance of tactical judgments against the number of correct responses they received on the Vandenberg and Kuse (1978) Mental Rotation Test, a measure of spatial ability. Analysis revealed a significant positive correlation of judgment performance with mental rotation score ($r = .45, p < .01$), indicating that as participants' spatial ability increased, their overall performance in making tactical judgments increased as well.

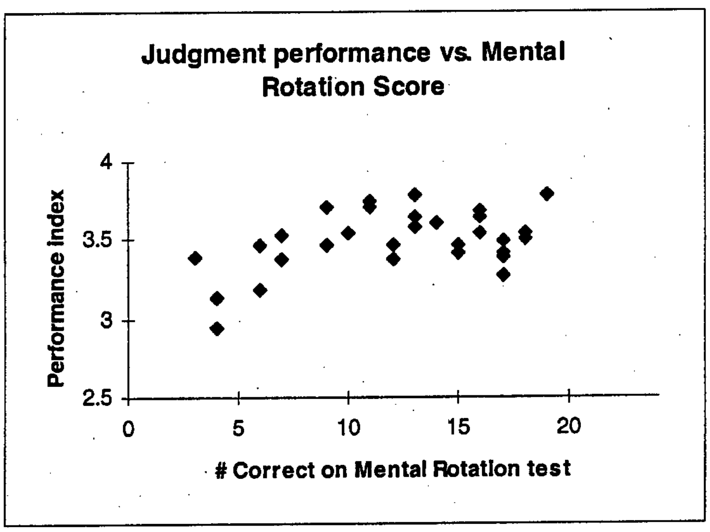

Figure 18. Plot of participants' mean judgment performance versus Mental Rotation Test score.

Accompanying this positive correlation between judgment performance and mental rotation score was a significant negative correlation between overall judgment response time and participants' mental rotation scores, $r = -0.37, p < .04$ (see Figure 19). This indicates that with higher spatial ability, participants' response time to tactical judgments correspondingly became faster. We anticipated that the role of mental rotation might be different within the interactive display, within which participants could physically rotate their viewpoint, and within the exocentric display with which they could not. Hence, the correlations within these two displays were explored separately.

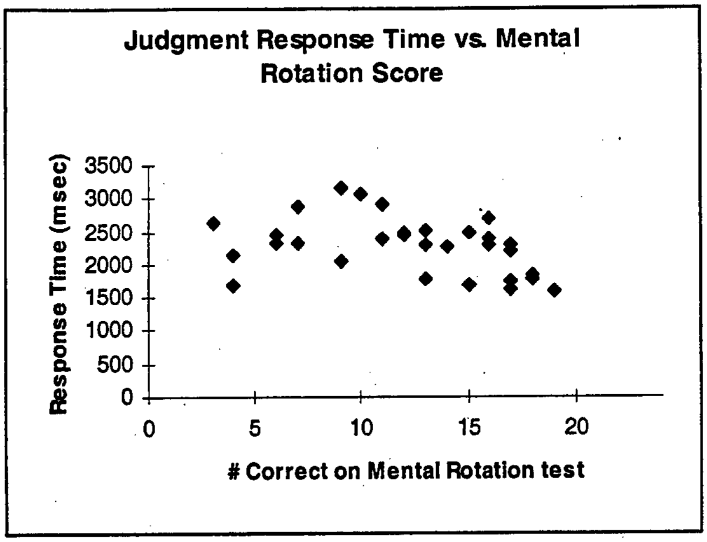

Figure 19. Plot of participants' mean response time versus mental rotation score.

Within 3D Perspective Display

Within the 3D perspective display format, a correlation was run between participants' mean judgment performance and mental rotation score. Results indicated a nonsignificant trend toward better overall performance of tactical judgments with higher spatial ability scores, r = .34, $p < .06$. This result is consistent with that shown in Figure 19, which is collapsed across all display formats.

To gain a better understanding of how the participants' use of terrain lighting in the 3D perspective display relates to both their tactical judgment performance and spatial ability, correlations were subsequently run between participants' mean judgment performance, mental rotation score, and mean use of terrain lighting and shading. Results did not indicate significant correlation between the use of the terrain lighting feature and either their mean judgment performance (r = .08, $p > .65$), or their Mental Rotation Test score (r = .21, $p > .26$).

Analysis was then concentrated on those circumstances (within the 3D perspective display) when terrain lighting was used most frequently, in order to determine what, if any, performance benefits arose from its usage as well as its relationship to participants' spatial ability. Results did not indicate significant correlations between participants' performance of mobility judgments with either their use of terrain lighting and shading (r = -0.23, $p > .21$), or their mental rotation score (r = 0.26, $p > .16$). Likewise, there was no significant correlation between participants' use of the terrain lighting feature and their mental rotation score, r = 0.10, $p > .59$.

Similar to results found when examining relationships among variables within mobility judgments, correlations between participants' performance when making LOS judgments with either their use of terrain lighting ($r = -0.004, p > .98$), or spatial ability ($r = 0.188, p < .31$) were not statistically significant. Analysis also failed to show a significant correlation between participants' use of the terrain lighting feature (when they made LOS judgments within hilly terrain) and their mental rotation score, $r = 0.103, p > .58$.

Within 3D Interactive Display

Analyses similar to those discussed within the 3D perspective display format were also performed, focusing exclusively on the 3D interactive display format. Collapsing across all three tactical judgment types and both flat and hilly terrain, there was a significant correlation between participants' mean judgment performance and their mental rotation score, $r = .37, p < .04$. Once again, this result is consistent with the correlations of judgment performance and mental rotation score within the 3D perspective display, as well as collapsed across all displays. As participants' spatial ability increased, indicated by higher scores on the Mental Rotation Test, their performance of tactical judgments likewise increased.

Analyses were also conducted on the relationship between participants' performance and their use of terrain lighting and shading in the 3D interactive display format. Results did not show a significant correlation between either participants' use of the lighting feature and their mean judgment performance, $r = -0.19, p > .29$, or their mental rotation score, $r = -0.04, p > .82$.

Also of interest within the 3D interactive display were relationships between participants' use of the display interactivity and their overall performance in making tactical judgments. Participants' use of the display interactivity was quantified by calculating the mean number of maneuvers made during trials when the interactive capability was available. Results did not show a significant correlation of overall judgment performance to control activity in the 3D interactive display, $r = 0.11, p > .57$. However, there was a nonsignificant trend toward a negative correlation between participants' control activity and their score on the Mental Rotation Test, $r = -0.33, p < .07$, shown in Figure 20. This result indicates that with higher scores on the Mental Rotation Test of spatial ability, participants maneuvered less within the 3D interactive display.

Similar to the analyses within the 3D perspective display, the focus was narrowed to those trials in which the use of the terrain lighting feature in the 3D interactive display was most prevalent, namely, within hilly terrain when mobility and LOS judgments were made. For mobility

judgments, results did not indicate significant correlations between participants' use of terrain lighting and shading with either their overall performance in making mobility judgments, (r = 0.09, $p > .61$), or with their performance in the Mental Rotation Test, r = 0.05, $p > .79$. Results also did not show a significant correlation between participants' mobility judgment performance and their Mental Rotation Test score, r = 0.17, $p > .36$. When participants' use of display interactivity was examined while they made mobility judgments within hilly terrain, no significant correlations were found between the amount of control activity and either judgment performance, r = -.22, $p > .24$, or Mental Rotation Test score, r = -.26, $p > .15$. However, the inverse relationship between participants' control activity when they made mobility judgments and their score on the test of spatial ability is consistent with the correlation of .37 reported previously, when the data were collapsed across all judgments within the interactive display format.

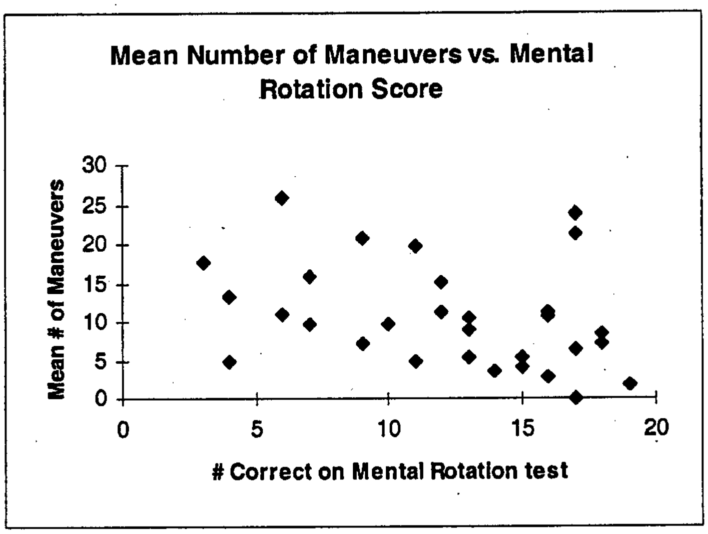

Figure 20. Plot of participants' average control activity in 3D interactive display against spatial ability.

Results from analyses of LOS judgments within hilly terrain of the 3D interactive display did not show a significant correlation of participants' mean performance of these judgments to their scores on the Mental Rotation Test, r = .24, $p > .19$. However, their judgment performance did correlate significantly and negatively with their use of terrain lighting and shading, r = -0.45, $p < .01$ (see Figure 21). (Because of overlap in the mean values of 30 participants, only 14 data points are plotted in Figure 21.) These results indicate that as participants' use of terrain lighting increased, their performance in making LOS judgments within hilly terrain decreased. Participants' use of the terrain lighting and shading did not correlate significantly with their scores on the Mental Rotation Test, r = -0.28, $p > .12$.

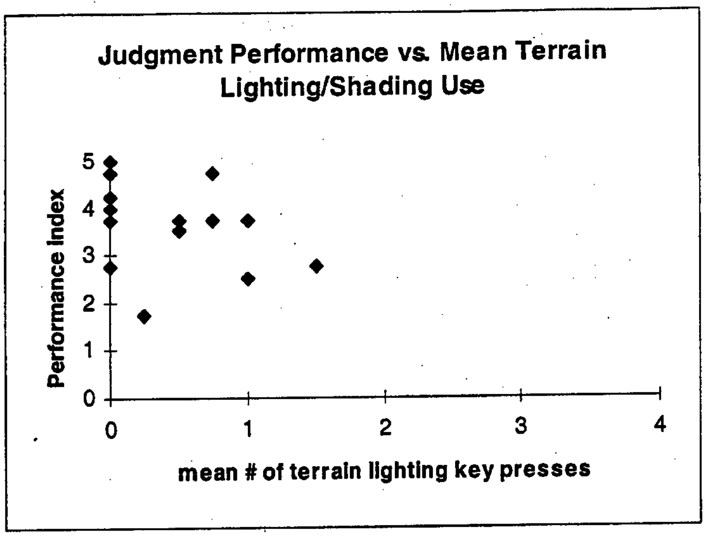

Figure 21. Plot of participants' average performance of LOS judgments against average use of terrain lighting and shading.

Participants' use of display interactivity when making LOS judgments, although not correlating significantly with mean judgment performance, r = -.040, $p > .83$, showed a nonsignificant trend toward a negative correlation with their scores on the Mental Rotation Test, r = -.33, $p < .07$. This result parallels similar findings within mobility judgments as well as collapsing across all tactical judgments, showing that as participants' performance in the test of spatial ability increased, their use of display interactivity decreased.

Participants' Comments

Upon completion of experimental trials and debriefing, participants were asked for their comments regarding the study. To stimulate dialogue, the experimenter asked participants the following general questions:

1. Do you feel that the judgments you were asked to make were indicative of judgments commanders are faced with in real-world battlefield situations?

2. What were your opinions regarding the display functionality provided to you? and

3. Do you have any thoughts about how to improve the display formats for future studies?

Altogether, 49 comments were received, which could be categorized as addressing issues related to tactical judgments, display format, and functionality. The actual comments are tabulated in Appendix B.

Generally, participants felt the experimental judgments were indicative of those actually made by commanders in tactical situations. By focusing these judgments on different echelons of command and perhaps incorporating more aspects of the battlefield environment (i.e., vegetation, units' available resources), officers felt these judgments could even more closely approximate real-world situations.

Overall, officers would have preferred more information (i.e., finer resolution in contour intervals, grids for estimating distance) in each of the three display formats. Comments suggested that participants felt most comfortable with the 2D contour display, remarking that it most closely resembled their current terrain maps used in the field. Participants' comments suggested a general dislike for the 3D static perspective display format. Several officers felt it provided very little helpful information for making tactical judgments. Participants' consensus on the 3D interactive display format, however, was that it proved useful, particularly when making LOS judgments.

Although finding the 3D display interactivity helpful, several officers would have preferred having the capability of real-time movement through the terrain in order to investigate different travel routes. Mixed comments were received regarding the utility of the terrain lighting and shading feature. Just as some officers felt the feature disambiguated some of the information provided in the color-coded terrain representations, others felt it was counter-productive in the sense that it either provided them with no additional information about the characteristics of the terrain or displayed characteristics that seemed contradictory to their preconceived notions. For instance, what may have appeared to an officer as a hilltop in the color-coded terrain representation now appeared as a saddle when the terrain lighting and shading were used.

DISCUSSION

The goal of this study was to gain a better understanding of which aspects of display design can prove most beneficial to commanders when they visualize the battlefield. Since the study was an initial effort within this domain, it also provided a chance to explore both the general types of tactical judgments that commanders need to make concerning the battlefield situation, as well as how commanders may or may not use different interactive tools to assist them in making these judgments. Feedback from officer participants indicated that the judgments

asked of them in this study, although sampling a limited aspect of battlefield visualization information (viz, terrain), are representative of judgments actually made in the field. Feedback from participants concerning the interactive tools made available to them in the study was mixed and is discussed later in more detail with respect to participants' individual differences.

Distinct performance trade-offs existed between the type of display format and the tactical judgments that officers were required to make. The costs and benefits of the display formats (in terms of dimensionality, frame of reference, and interactivity) are discussed next with respect to each of the three tactical judgment types.

Mobility Assessment

Based upon a review of the literature summarized in Table 2, we predicted relatively equal performance of judgments of mobility assessment with either the 2D or 3D display format. Parallel to findings in aviation domains regarding judgments relative to a surface (Boyer & Wickens, 1994; May, Campbell, & Wickens, 1996), our results did not seem to show a distinct benefit to either the 2D or 3D display for tactical judgments regarding mobility across terrain. Participants in this study, similar to air traffic controllers viewing plan views of the air space, are very experienced in viewing battlefield terrain with 2D maps and visualizing the 3D terrain from the contour representations. Although this process may require more cognitive resources than those required by an integrated, 3D representation of the terrain, the resulting ambiguities of the latter may be costly enough to outweigh these benefits.

Terrain type exerted a significant effect on the officers' ability to assess mobility. Not surprisingly, the officers took longer to respond and made less accurate assessments of troop mobility in more mountainous terrain. This performance decrement was observed with all three display formats. A contributing factor to this decrease in performance with more mountainous terrain may have been the increasing need to consider pre-defined mobility rules in making this type of judgment. Mobility was virtually unconstrained in flatter terrain, so officers did not have to consult the pre-defined rules nearly as frequently as in more mountainous situations. Comments from officers indicated that although these rules were available for reference throughout the study, they were rather detailed and difficult to recall easily. In addition, officers mentioned that from past experience, they had (to an extent) their own conceptions of what traversable or non-traversable terrain looked like, which may have differed from the concept prescribed in the specific rules used for this study. A possible design enhancement to assist officers in making this particular type of judgment could be a symbolic overlay (such as color

coding or hachure lines) of mobility constraints (i.e., restricted, severely restricted) on the depicted terrain. This enhancement relieves officers of the cognitive effort required in translating a mathematical rule of what restricted terrain "is" into what it should "look" like and then mapping it on the given contour or 3D representation.

Concerning the effects of frame of reference on making mobility judgments, we predicted a performance benefit for the exocentric display (see Table 2). Results from the current study indicated that officers relied more heavily on the exocentric display of the terrain than on the egocentric view provided in the 3D interactive display. This preference seems logical since the judgment being made requires consideration of travel along various paths, essentially covering a substantial area of battlefield. Mobility judgment performance remained virtually the same in both the 3D perspective and interactive formats, indicating that the immersive capability did not provide an added benefit to officers in deciding which paths over terrain were viable routes for travel from ones that were not. When more closely examining participants' use of the interactive tools provided them, we found that officers did not employ the interactive tool much for assessing troop mobility in hilly terrain and even less when assessing mobility in flatter terrain. Officers' judgment performance decreased in the condition (i.e., hilly) when the egocentric view was more heavily used. This finding is similar to results from studies within aviation, which support increasing levels of exocentricity for tasks involving location of objects relative to terrain or hazards (Wickens & Prevett, 1995; Olmos, Wickens, & Chudy, 1997). In contrast to the limited use of the viewpoint tool, officers did use the other interactive tool (the terrain lighting and shading feature) quite frequently when they assessed troop mobility. However, the results did not indicate any performance benefit from its use.

Relative Position of Units and or Destinations

For this particular judgment, officers were required to determine the distance between two objects "as the crow flies," essentially disregarding vertical development of terrain (i.e., vertical axis). Therefore, these judgments were more akin to pilots' judgments of lateral separation of aircraft at fixed altitudes (Tham & Wickens, 1993). As shown in Table 2, we predicted a distinct benefit for the 2D display when making this type of judgment, and a clear benefit was seen with the 2D display format in judgments involving the relative position of units and or distance between a unit and a specified destination. Results showed significantly better performance in terms of both response time and accuracy for the 2D display relative to the two 3D formats for these judgments. This finding is consistent with several findings within the domains of aviation and air traffic control, showing benefits of the 2D display in determining precise location in 3D

space (Merwin, O'Brien, & Wickens, 1997; Olmos, Wickens, & Chudy, 1997; Olmos, Liang, & Wickens, 1997; Wickens & Prevett, 1995). These costs of the 3D display can probably be attributed to ambiguities along the LOS (McGreevy & Ellis, 1986; Gregory, 1977). Since officers were instructed to base their judgments strictly on lateral separation, the perspective display may have created confusion as to the units' and or destinations' exact location, requiring officers to disambiguate an object's precise location along the lateral axis from its location along the vertical axis.

Officers' performance in estimating distances between units and or destinations remained virtually constant, regardless of vertical development in terrain. This finding seems logical, since the vertical axis is essentially irrelevant to this judgment task. One would then also predict that the officers' use of the terrain lighting and shading feature would be limited when making these tactical judgments. Indeed, the frequency of its use by officers when making this judgment was considerably less in comparison to its frequency of use with either LOS or mobility judgments.

No strong predictions were made regarding the effects of different frames of reference on making distance judgments (refer to Table 2). The current results indicated relatively equivalent performance between the 3D static perspective display and the 3D interactive display. The added capability of an egocentric viewpoint provided neither an added benefit nor a cost for performance of distance judgments and was rarely used. This finding differs from studies within the aviation domain that have shown a benefit for the egocentric viewpoint in making precise location judgments. However, many of the location judgments assessed in the aviation domain assessed elevation and azimuth, rather than precise location. Furthermore, the fact that the current study did not show a benefit for the egocentric viewpoint may, in part, be attributable to a feature inherent in the design of interactive displays. Participants were given a scale, marking a 1-kilometer distance, in the lower left-hand corner of the 2D contour display and in the middle, right-hand side of the 3D perspective and 3D interactive display formats. When officers immersed themselves in the terrain, the 1-kilometer scale that appeared in the middle, right-hand side of the perspective display remained in this position on the screen. The presence of this scale could have possibly misled some officers into estimating distances of objects viewed in the immersive display according to this erroneous measure, although their expectation of the immersive view as presenting a "zoomed in" representation of a selected portion of the perspective view would suggest that objects depicted within this view are much closer. At least one officer's comments indicated a degree of confusion about the presence of the 1-kilometer scale in the immersive display format. Finally, our analysis has no way of revealing the extent to which the distance judgments were made

while the participant was in the egocentric view. It is possible that most judgments might have been made when participants were in the exocentric mode of this interactive display.

LOS Judgments

From the research findings presented in Table 2, we did not predict a distinct benefit for either the 2D or the 3D perspective display format for assessing LOS visibility, which requires accurately determining the relative position of targets to one another as well as the intervening terrain. Examining the effects of display dimensionality on the officers' ability to assess LOS visibility, we found relatively equivalent performance between the 2D contour display and the 3D perspective format. Separating the components of judgment performance into accuracy and confidence ratings revealed a slight benefit in accuracy for the 2D display. A possible explanation for this benefit may be partly attributable to the officers' extensive background in determining LOS visibility from traditional 2D maps, which the 2D electronic format most closely matches.

With regard to the effects of frame of reference on making LOS judgments, we predicted a benefit for the egocentric viewpoint, provided by the 3D interactive display. Results from the current study showed a substantial difference in accuracy between 3D fixed and the 3D interactive display, favoring the latter. However, officers took longer to respond to LOS judgments in the 3D interactive display than in either the perspective or 2D displays, which is attributable in large part to the added amount of time required to select a position and orient within the display. Comments from officers suggested that they often had a preconceived notion about the visibility of a given unit, and when the immersive capability was provided, it confirmed their suppositions. This is reflected in the finding that officers used the interactive capability to immerse themselves in the terrain most frequently when making LOS judgments. Note, however, that the immersive capabilities not only improved confidence as the officers' comments suggested (see Figure 12) but also improved accuracy independently of confidence (see Figure 11).

It is also important to note that officers were actually asked to make two different types of LOS judgments: (a) determining visibility from a point and (b) determining visibility to a point along a given path. When LOS judgments were broken into these two components, results showed that participants were less accurate and took longer when answering questions regarding visibility along a path. This increase in response time was magnified in the 3D interactive display format.

Judgments of visibility to a point along a path require visualization of terrain at various locations along a given travel path, possibly causing officers to maneuver more in the 3D interactive display in order to position themselves at various locations along the given path. This explanation is consistent with previously discussed findings of longer response time and more maneuvering in the 3D interactive display, when collapsing across both LOS judgment types. However, the longer response time seen with the 3D interactive display for determining visibility to a point along a given path was not coupled with a corresponding benefit in judgment accuracy.

Overall, it can be concluded that the display format most appropriate for battlefield commanders is highly task driven. Also of interest are individual differences among commanders and the possible influences these differences may have had on the utility of the different display formats and their interactive capabilities.

Individual Differences

Results from officers' performance of Vandenberg and Kuse's Mental Rotation Test (1978) provided additional insight into officers' performance in making battlefield judgments. As officers' spatial ability increased (as measured by their scores on the Mental Rotation Test), so did their overall performance of the three tactical judgments. Interestingly, more specific examination of mobility and LOS judgments within the 3D displays did not reveal any systematic relationships between officers' spatial ability and judgment performance. One explanation for this inconsistency becomes apparent when considering the following situation, depicted in Figure 22. Figure 22 represents a possible pattern of participants' data that would result in correlations consistent with those found in the present study. For example, a participant with low spatial ability may score high on LOS questions but low on mobility questions. Another participant, with medium spatial ability scores well on mobility judgments yet low on LOS judgments. A third participant with high spatial ability scores well on mobility judgments and even better on LOS judgments. Looking within either LOS judgments or mobility judgments exclusively, no correlation exists between judgment performance and spatial ability. However, when averaged over judgment types, a positive correlation results.

When provided with interactive viewpoint tools, officers with higher levels of spatial ability had a trend toward less frequent use (maneuvering). It seemed that officers were relying more on their own perceptual and cognitive strengths to make judgments rather than taking the time and effort to use the display functionality. Since performance did not improve with greater use of the interactive tool of viewpoint positioning, it is possible that officers with lower levels

of spatial ability might have compensated for these lower levels by increasing tool use, thereby preserving performance.

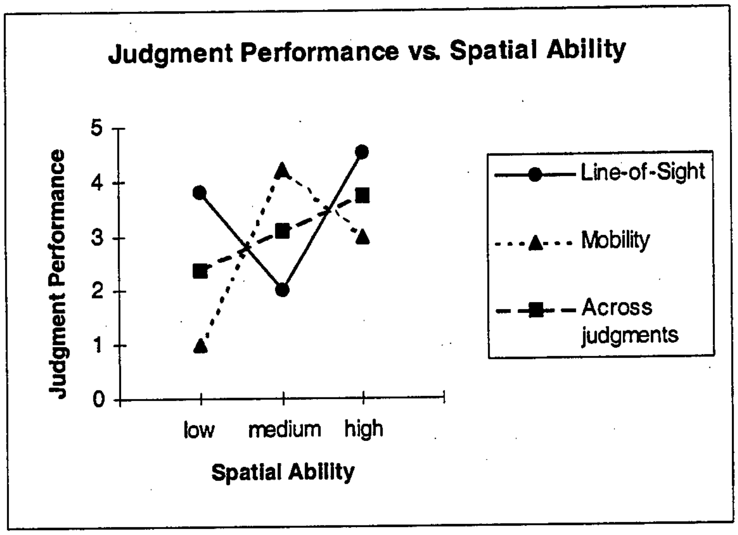

Figure 22. Plot of three participants' performance of LOS and mobility judgments as a function of their level of spatial ability.

Officers' use of the terrain lighting and shading feature increased as the vertical development of the terrain increased, particularly in making mobility and LOS judgments. However, increased use of this tool did not offer any performance benefits and even correlated with poorer performance of LOS judgments within the 3D interactive display of hilly terrain. Since there was no relationship between officers' spatial ability and their use of the lighting tool, unlike the interactive tool, those officers with lower spatial ability did not seem to be using the tool more to compensate for their deficiencies. In addition, the lack of a relationship between participants' spatial ability and their performance of the LOS judgments seems to suggest that an aspect of the lighting tool itself may be contributing to the performance decrement. As several officers' comments suggested, perhaps the view of the terrain presented when activating this feature contradicted officers' preconceptions. Although their preconceptions may have been correct, officers may have discounted them, placing unwarranted trust in the lighting tool and thereby producing an erroneous response to the experimental question. Their trust in the tool is partly reflected by results that indicate an increase in terrain lighting and shading usage for those situations in which an understanding of the terrain is highly critical (i.e., mobility and LOS judgments in hilly terrain).

These findings lead to an important distinction to be made between tools and displays that give one greater confidence but not better performance and those that also improve performance. When the results from the current study are examined (see Figures 11 and 12), participants' performance decreased when making distance judgments within the two 3D displays, yet their confidence (in having made accurate judgments) remained high. On the other hand, as previously mentioned, as participants' confidence in answering LOS questions improved when using the 3D interactive display, their performance substantially improved as well. In short, confidence cannot always be trusted as a valid measure of usability.

CONCLUSIONS

In this experiment, we have taken the initial steps toward developing an understanding of commanders' needs when they visualize terrain and the battlefield environment. With the rapid development of advanced technology in all aspects of military combat, this understanding can distinguish those types of technology that may prove most beneficial from those that may not. The results of our study tended to show that the benefits provided by a given technology are task dependent. Incorporating interactivity into displays can enhance performance for some judgments; yet, as was shown with the terrain lighting and shading feature, "more" is not always better.

Further research can investigate ways of enhancing display formats to create one "format" that can offer "the best of both worlds" or in this case, the best of "three" worlds to officers. Such enhancements could possibly include grid line overlays in the perspective display to improve distance estimations or perhaps a single display with a rotating elevation angle to incorporate the benefits of the plan view with the more realistic 3D representation of terrain.

The commanders' battlefield environment is truly complex. Our study took a distilled view of one aspect (terrain) and its effects on battlefield planning. Unit composition, available resources, climate, and vegetation are just a few of the multitude of other factors that must also be considered by the commander in real-time battlefield situations. By including more of these aspects in situations where commanders must make judgments in "real time," the questions about what benefits technology can truly offer the commander can then be better answered.

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APPENDIX A

MOBILITY RULES

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1. Unrestricted terrain is defined as

    a. Flat to moderately sloping terrain, with gradients of less than 200 m in elevation per 2000 m.

    b. The maximum speed over unrestricted terrain is 10 kph.

2. Restricted terrain is defined as

    a. Terrain with moderate to steep gradients, ranging from 200 m in elevation per 2000 m to 200 m in elevation per 1000 m.

    b. The maximum speed over restricted terrain is 4 kph.

3. Severely restricted terrain is defined as

    a. Terrain with steep gradients of more than 200 m in elevation per 1000 m.

    b. The maximum speed over severely restricted terrain is 1 kph.

4. Terrain with gradients greater than 200 m in elevation per 800 m are not capable of being traversed.

5. Small towns are considered obstacles and not capable of being passed through.

6. Rivers are capable of being crossed but will delay travel time by 1 hour.

7. The maximum speed on roads is 20 kph.

8. Firing range is defined as the maximum distance, measured "as the crow flies," one unit's weapons are capable of firing to penetrate another unit and/or specified location. The maximum range of fire is 3000 m.

<u>Note</u>. For the purposes of this experiment, judgments regarding the location of one unit as "closer to" or "farther away from" another unit and or destination should be answered in terms of their relative distance "as the crow flies."

Map Information

Changes in terrain elevation are provided through a continuous color-coding scheme, ranging from pale yellow (for lower elevations) to burnt red (for the highest elevations). Each individual color interval indicates a 200-m change in elevation. In addition, contour lines, delineating 40-m changes in elevation, will be provided for those maps in which the elevation of

the entire area of flatter terrain is depicted within a single color interval. Terrain shading is also provided for perspective displays of both hilly and flatter terrain. Display viewers are capable of toggling between these displays and the color-coded contour displays. A scale is provided in the bottom left corner of every map, marking a length of approximately 1 inch as equivalent to a distance of 1 km on the map. Map symbology is defined as the following:

(1) Roads = black lines
(2) Rivers = blue lines
(3) 40-m contour intervals = gray lines
(3) Travel paths = red lines (labeled accordingly)
(4) Units = rectangular boxes (labeled accordingly)
(5) Destinations = circles (labeled accordingly)
(4) Towns = cluster of three or more red boxes

APPENDIX B

PARTICIPANTS' COMMENTS

PARTICIPANTS' COMMENTS

Judgments

1. Judgments were good and indicative of actual judgments made.

2. LOS questions are especially pertinent, as well as battlefield synchronization questions, such as "Who will get there first?"

3. Judgments should focus on different echelons (i.e., company needs as well as platoon needs). Examples of experimental questions to accomplish this could be, "Is this an avenue of approach for a company? platoon? battalion?"

4. Questions should ask things about more detailed rates of movement, specifically "How long will it take?" Other questions to include could be, "What point affords hiding the best?" and "What point is least visible?"

5. When shooting at the enemy during combat situations, it is important to consider both LOS and firing range, not them singularly.

6. Locating intervisibility lines is slightly different than LOS, but also important to consider. For example, a small ridge can have just enough elevation to break LOS. A race to these "intervisibility lines" is important in combat.

7. At times, it was ambiguous and seemed that all travel paths shown could be taken to a specified destination.

8. There is quite a bit more to consider with regard to battlefield planning in addition to terrain, such as vegetation.

<u>Mobility Rules</u>

1. Remembering the mobility rules, although available during the experimental session, was difficult. It seemed much easier to look at the terrain gradients and rely upon an understanding of maps to make judgments.

2. Officers have a general sense of what type of terrain is or is not traversable.

3. A few of the mobility rules required considerable attention to detail. It was helpful to pass them out a day beforehand.

4. It would be nice to have immediate feedback of performance on judgments.

5. It would have been more helpful if participants were given a "picture" or image of what a contour interval that is too steep actually is for the purposes of this study.

Display Formats

Symbology

1. Either tick marks or a grid overlaid on the maps would have been helpful for determining if units are within range.

2. It would have helped to have elevations and high points of terrain marked numerically.

3. The small "x's" used to designate high ground for flatter displays should be done for the steeper terrain displays also.

4. It was hard to tell if a path was or was not traveling on a road. It would be less ambiguous if the roads were depicted wider than the paths.

5. In order to better understand the constraints of the terrain, a color-coded overlay could be used with the following designations: "go" = green, "slow go" = yellow, and "no go" = red.

6. It would be more helpful if you could "click and drag" the 1-km scale (displayed on each map display) over to the area of the terrain of interest.

7. When immersed in the terrain, the appearance of the 1-km scale is confusing and should be removed.

Contour Intervals

1. With such large contour intervals (200 m), there is no way of knowing if units can really see each other or not—not good enough tactical resolution.

2. Contour intervals of 40 m (depicted in flatter terrain) are never seen in actual Army maps. In order to supply an adequate amount of information, 10-m intervals would be more appropriate.

3. The satellite view of the terrain depicted in the displays is too far to tell what is actually happening on the terrain.

2D Display

1. Actual paper maps provide more help than the 2D electronic display format provided.

2. Making estimations felt most comfortable with the 2D display (of flatter terrain).

3. 2D display was most useful because it most closely resembled the map format officers are most used to reading.

4. The 2D map display provided the most information and was the best format to use for making judgments.

3D Perspective Display

1. The 3D static map seemed to be good only with severe terrain and not as useful as the interactive display.

2. It would feel much more comfortable making judgments with a paper map and then looking at the terrain in the corresponding 3D view.

3. The 3D perspective display was useless in providing additional information and was virtually the same as the 2D display.

3D Interactive Display

1. The 3D interactive was very useful for verifying LOS questions.

2. An ideal format would be to toggle between the 2D display (for making distance judgments) and the 3D immersed point of view in a split screen format.

3. Using the technology of the 3D interactive display seemed more comfortable as you went through the trials.

Interactive Capabilities

Terrain Lighting and Shading

1. At times, it was difficult determining which area of terrain was actually higher. The terrain lighting disambiguated some of that.

2. Terrain lighting and shading for flat terrain was useless. Coloration of the terrain was a better feature and provided more information.

3. Terrain lighting seemed counter-intuitive. Highlighted areas looked like lower points and darker looked like high ground when toggling between views with color-coded contours and terrain lighting. Because of this, it was hard to trust when making judgments.

4. The lighting feature was most helpful with 3D perspective display.

3D Display Interactivity

1. It would have been better to allow for more freedom of movement within the display, so that you can follow your way along specified paths.

2. The interactivity of the 3D display helped to confirm or disconfirm preconceived notions of what the correct answer should be.

3. The capability of changing pitch inside the 3D interactive display did not help much. No additional information was provided by using it.

4. The interactivity was use primarily for LOS judgments and not as much for other judgments.

5. The interactive capability is better because you can actually SEE how big or steep terrain is that is depicted in the other views.

6. It would be a great benefit to be able to move up in elevation from the original point once in the display (e.g., pop-up 20 m or 50 m).

7. It would be helpful to "click" two areas on the terrain and have the computer automatically calculate the distance between them (e.g., Janus display functionality in which planning mode range fans are automatically calculated).

8. The 3D interactivity does sharpen map reading skills and terrain visualization. It would seem helpful as a once-a-month training or refresher exercise.

<u>Display Devices</u>

1. Clicking and dragging the compass (provided in the interactive display) to the appropriate heading would have been less cumbersome than pressing the arrow keys.

2. A trackball would be easier to operate than a mouse.

3. It is awkward shifting between mouse and keyboard devices when using the interactivity of the 3D display.

4. Time is critical in a lot of battlefield activities, so devices must be handy, user friendly, and accessible in quicker, smaller packages. A mouse and keyboard combination is too big.

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13. ABSTRACT *(Maximum 200 words)*

To gain a better understanding of the effects of display dimensionality and frame of reference on battlefield commanders' ability to understand the constraints of battlefield terrain, we constructed three electronic map displays, depicting both flat and mountainous terrain, and studied their effects on making various types of tactical judgments. U.S. Military Academy officers were presented with a two-dimensional (2D) contour display, a three-dimensional (3D) static, exocentric display, and a 3D interactive display of various battlefield situations (i.e., friendly and enemy units, travel paths, destinations) and were asked to make judgments regarding unit mobility across the depicted terrain, relative distances between units and or destinations, and line of sight (LOS) to specified locations. Officers were asked to make judgments as quickly and accurately as possible, while taking into account pre-defined mobility rules that had been distributed before the actual experimental session and were available throughout the study. In addition, officers were asked to provide verbal confidence ratings of having responded accurately to individual judgments. Results showed performance trade-offs in making the three tactical judgments, depending upon electronic map display format used. Distance judgments were best served by the 2D display, while the 3D interactive display best supported LOS judgments. Officers' performance in making mobility judgments was affected by the degree of vertical development of the depicted battlefield terrain. The relationship of participants' spatial ability to their performance in making tactical judgments and using interactive display capabilities is also discussed. When participants were provided with interactive viewpoint tools, there was a trend toward less frequent use (maneuvering) for officers with higher levels of spatial ability. It seemed that officers were relying more on their own perceptual and cognitive strengths to make judgments rather than taking the time and effort to use the display functionality. Since performance did not improve with greater use of the interactive tool of viewpoint positioning, it is possible that officers with lower levels of spatial ability might have compensated for these lower levels by increasing tool use, thereby preserving performance.

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